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Review

Digital Technologies for Quality Assurance in the Construction Industry: Current Trend and Future Research Directions towards Industry 4.0

Frank Ato Ghansah [1,*] and David John Edwards [2]

[1] Division of Construction, Property and Surveying, School of the Built Environment and Architecture, London South Bank University, London SE1 0AA, UK
[2] Department of the Built Environment, Birmingham City University, Birmingham B4 7XG, UK; drdavidedwards@aol.com
* Correspondence: frank.ghansah@lsbu.ac.uk

Abstract: Despite the growing rich and fragmented literature focusing on quality assurance (QA) and Industry 4.0, the implementation of associated individual digital technologies has not been fully evaluated and synthesised to achieve adequate QA in the construction industry; hence, it has received limited focus. This study, thus, aimed to organise, evaluate, and synthesise the current literature on individual digital technology applications in QA in the construction industry and propose future research directions. A literature review approach was adopted for this study along with Deming's cycle framework to address four research questions: (1) What is the status of the state-of-the-art in the literature? (2) What digital technologies have been applied for QA in the construction industry? (3) Which areas in QA processes have experienced digital technology applications, and what are the applications? (4) What are the limitations of the existing studies and future research directions of digital technologies for QA in the construction industry? The findings showed an increasing trend of research on digital technology for QA in construction since 2017. This cuts across 23 countries with six different research methods published across 18 different publication sources. Four categories of digital technologies were revealed to have been adopted for QA in construction based on the functionality of the technologies: data collection technologies, decision-oriented technologies, collaborative technologies, and transparency and security-related technologies. Evaluation with Deming's cycle framework revealed that digital technologies have a high level of application at the "do" phase, improving the quality management process during construction towards achieving pre-stated quality requirements. This includes mostly collaborative technologies, consisting of BIM technologies. Limitations of the existing studies were further identified, and this led to five research directions: interoperability of technology development, integrated digital technologies for QA of prefabricated and modular construction, integrated digital technologies for QA of cross-border construction logistics and supply chain, digital innovation for sustainable QA, and moving beyond the technical solution. The study showed a significant contribution to both academia and the industry in the built environment.

Keywords: construction industry; digital technologies; Industry 4.0; quality; quality assurance

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1. Introduction

The construction sector has been noticed to be underperforming, and projects are noticed to be completed late, over budget, and with low-quality standards [1] compared with other industries. For example, the cost of poor quality is more than the combined profit of the construction companies in the sector. In the UK, it has been estimated that better quality management could save the construction industry up to GBP 12 bn a year [2]. The US construction industry expended USD 1502 bn in 2004 on total construction costs and USD 75 bn on rework costs [3]. This rework could be linked to construction products failing to meet customer requirements or when the completed works fail to comply with the actual contract [4]. The direct poor quality cost was estimated to be 21% in Turkey [5], 8% in Uganda [6], 9.4% in Sweden [7], 4% in Australia [8], and 5.8% in the UK [9]. It has been noticed that quality has been a critical issue in the construction industry as it involves a systematic process and procedural activities for determining that construction projects meet quality requirements, including the client's requirements, regulatory requirements, and fit for the purpose [10,11]. It is a desirable feature of a construction project by all stakeholders in the construction industry and is premised on the adequacy of the quality assurance (QA) system.

QA is a set of activities aiming to demonstrate that a product or service meets all quality requirements and can satisfy the end user [10]. According to the Project Management Body of Knowledge (PMBOK) [11], QA refers to the activities involved in managing quality on a project; hence, it is termed "manage quality". This study adopts the two definitions due to the commonality of the QA concept [10,11]. QA activities are carried out in construction projects to inspire the confidence of stakeholders in meeting the quality requirements before finally being delivered to the client for usage. QA ensures stakeholders that structures, components, materials, or systems meet pre-stated quality standards and will perform satisfactorily during their entire service life [12]. Compliance with quality requirements and documentation of achieved quality is essential in the construction industry [13]. This results from the joint actions of multiple participants, ensuring effective collaboration to ensure the right thing is done first and avoid errors. Though QA has been used synonymously or with quality control by scholars, it is imperative to acknowledge the differences in this study, as quality control is product-oriented and focuses on improving end products by identifying and fixing defects, involving specific teams that test the products [11,14,15]. However, quality control may also be an important aspect of QA processes, where individual finished sub-works are examined and tested to verify quality before proceeding to the next sub-works [16]. As this study seeks to investigate the systematic process and the procedural activities in ensuring that the construction project meets quality requirements, QA becomes the focus.

Nevertheless, there are still opportunities to improve the QA process in construction, considering the emergence of Industry 4.0 associated with the promotion of digital technologies. In the construction industry, QA processes have involved integrating a few digital technologies to ensure adequacy and effectiveness in managing quality [17]. This can be evident from the rapid adoption and integration of digital technologies into construction processes to ensure activity continuity amid the recent coronavirus disease (COVID-19) risks. Existing studies have focused on reporting the individual application of digital technologies to specific QA problems. These include the following: Tang et al. [18] argued quantitatively to understand the cost and time benefits of deploying terrestrial laser scanning (TLS) for construction QA. The result demonstrated that the TLS-based QA approach is more efficient than the conventional QA approach due to reduced data collection time. Ma et al. [19] highlighted the integration of Building Information Modelling (BIM) and indoor positioning systems to produce a web-based collaborative system to improve the QA process construction. The proposed system was noted to be robust for project stakeholders to follow rules of standards on managing quality whilst ensuring efficient collaboration and communication among the stakeholders. However, digital technologies in QA are generally at a low technology readiness level, with limited application and evaluation [20].

Despite the growing attention on integrating digital technologies into QA in the construction industry and its fragmented nature in literature, there is no systematic evaluation and synthesis of how the available individual digital technologies have been utilised for QA in the construction industry and how these technologies can effectively enhance QA activities in construction. This area has received limited attention in studies. Thus, the study aims to organise and identify the most relevant papers on digital technology applications for QA in the construction context via a literature review. Then, these identified papers are critically reviewed and synthesised to understand the adopted digital technologies for QA, the application areas, limitations, and the gap in the literature, which will help draft the roadmap for Industry 4.0 utilisation for QA in construction. Deming's cycle framework is adopted to guide in understanding the application areas of digital technologies for QA, with four interrelated phases in the QA processes: plan, do, act, and check. For this study, four main research questions are specifically addressed:

- What is the status of the state-of-the-art in literature?
- What digital technologies have been applied for QA in the construction industry?
- Which areas in QA processes have experienced digital technology applications, and what are the applications?
- What are the limitations of the existing studies and future research directions of digital technologies for QA in the construction industry?

To answer the questions, 103 articles related to the topic were collected from the Web of Science and Scopus databases, and 56 were selected for further critical analysis. The findings of this study contribute to enhancing the understanding of digital technologies for QA in construction, and this could promote research interest and industry support for comprehensive and cutting-edge research in this field.

2. Brief Overview

Quality is an important issue in the construction industry, as it involves a systematic process and procedural activities to ensure that construction projects meet quality requirements, including the client's requirements, regulatory requirements, and fit for the purpose [10,11]. It is a requisite characteristic for construction projects, as projects are executed based on requirements and are premised on effective QA practices [12]. QA defines the set of activities whose purpose is to demonstrate that a product or service meets all quality requirements as stated in the contract [10]. The PMBOK [11] referred to QA as "manage quality" after planning quality and before quality control. From the design to project delivery, QA practices are effectively conducted to ensure that processes and services meet contractual requirements, including the client's needs. Consequently, QA is premised on effective joint actions from multiple stakeholders related to a particular project [17]. This inspires the confidence of stakeholders that a structure, component, material, service, or system meets pre-stated quality standards and has a high probability of satisfying the customer during the entire service life [12]. Thus, the objective of QA is to independently ensure that activities of construction and its services are being performed following all contractual codes, specifications, and standards or government regulations. These regulations help to make it clear what safeguards must be put in place before a technology can be brought into widespread use to achieve quality. The regulations and standards could ensure that the technology is safe and ethical and does not infringe on workers' rights in achieving quality [21]. Thus, quality is verified through checks, inspections, and witnessing [12]. QA practices are conducted independently of the individual contractors, material suppliers, manufacturers, sub-contractors, and final users, but the results must be interrelated. Hence, effective collaboration and communication are paramount in conducting QA in the construction industry.

QA differs from quality control, though the terms are occasionally used in tandem. QA is process-oriented and focuses on improving processes and methodologies to develop a quality project by engaging every member of an organisation towards defect avoidance. In contrast, quality control is product-oriented and focuses on improving end products by identifying and fixing defects, involving specific teams that test the products [14]. As this study focuses on the systematic process and the procedural activities in ensuring that the construction project meets quality requirements, QA becomes the focus. Quality control may also be an important aspect of QA processes, where individual finished sub-works are examined and tested to verify quality before proceeding to the next sub-works [16].

The era of Industry 4.0, which is the integration of intelligent digital technologies into manufacturing and industrial processes [22], has imposed new challenges and opportunities to the construction QA processes by introducing digital technologies, which facilitate and improve the processes, leading to construction 4.0. These include enabling technologies, such as big data and analytics, industrial robots, the Internet of Things (IoT), artificial intelligence (AI), cloud computing, big data, robotics, and automation [23]. Construction 4.0 has then been referred to as using digital advancements to innovate and advance the construction industry [22]. Scholars have observed a transition in the focus of QA activities/practices/processes from only compliance orientation to improvement orientation and business management [24,25]. From the perspective of improving construction operations, processes, and management towards QA, digital technology adoption has been explored to some extent [26–28]. Li and Liu [29] and Pan et al. [30] examined the adoption of digital technologies for quality monitoring and checks in the construction industry. Other scholars have also applied digital technologies to improve the QA processes from a different context [31–33]. This has resulted in the new concept of Quality 4.0, which refers to the future of quality management in the Industry 4.0 paradigm and is defined as the digitisation of quality of design, quality of conformance, and quality of performance using modern/digital technologies [34–36]. Quality is broad and dependent on the execution of each construction task, the quality of design based on which structures are built, the quality of input resources (building materials and products, machines and equipment, and workers), the way of managing the resources, the quality of managing time and cost parameters, the quality of control processes, the quality of change management processes, etc. This study, thus, focuses on the use of digital technologies for every activity related to achieving quality in construction, that is, digital technologies for QA in construction. Figure 1 illustrates a framework of digital technology applications for ensuring quality requirements conformance during the construction phase of a project. Scholars have, therefore, conducted empirical studies to shift from product/process quality towards information quality in a smart manufacturing environment, the value of data quality in a digital environment, and technology-based solutions for exploring interrelationships in a complex QA process.

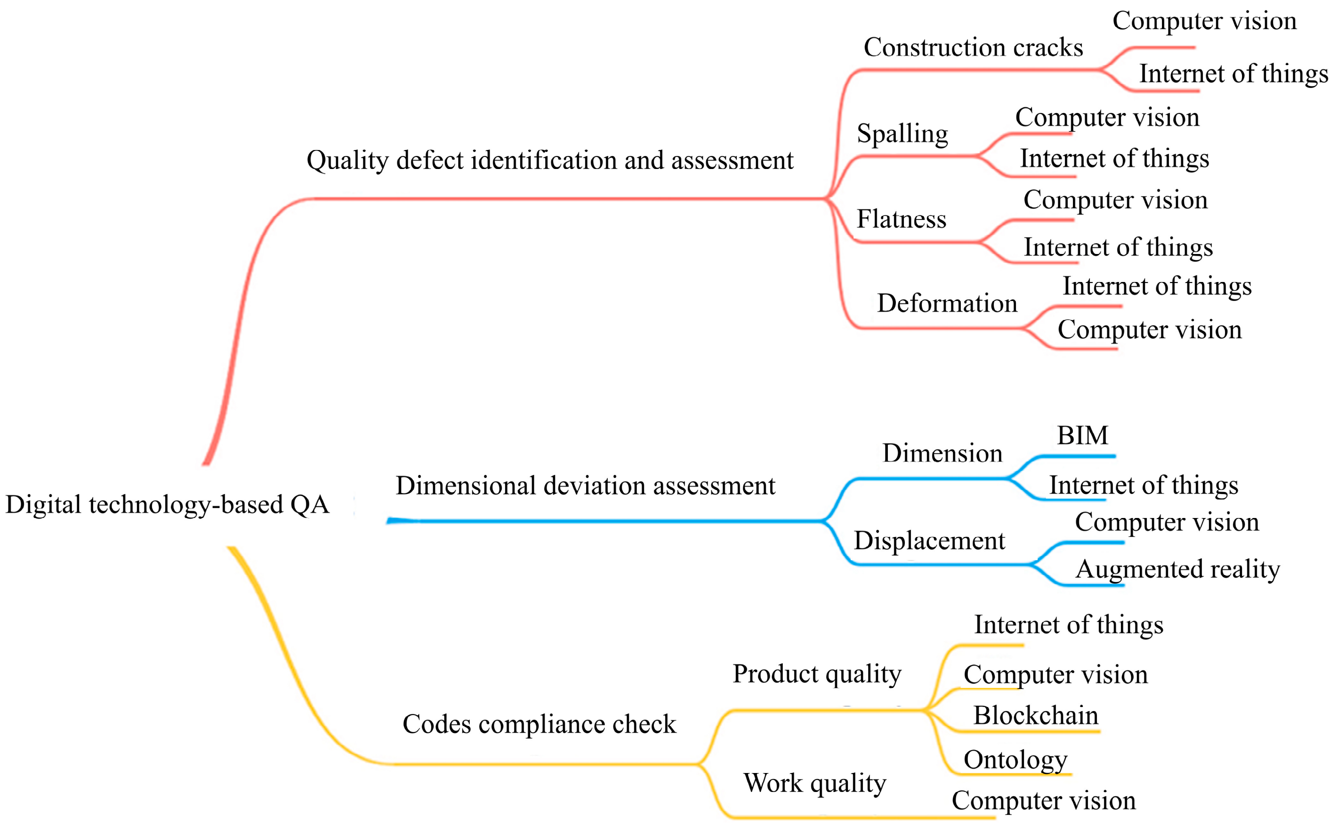

Figure 1. Digital technologies in QA in the construction industry (Adapted with permission from [17]).

A Framework for Understanding the Application of Digital Technologies for QA

Previous studies have demonstrated the effectiveness of adopting system approaches in understanding the complexities of digital technologies in construction [37,38]. A framework is needed to understand the digital technology application in QA processes in construction. This study extends the framework of Deming's cycle in QA [39], which consists of interrelated phases in QA to examine the research on digital technologies for QA. Deming's theory is adopted in this study to understand how digital technologies have been used to improve the QA processes in construction (i.e., to understand the application area of digital technologies in construction QA).

Deming's cycle is a continuous quality improvement model that consists of a logical sequence of four stages: plan, do, check, and act [PDCA] [40]. This model, compared with other models proposed by Cosby [41] and Juran [42], has the advantage of being helpful in all situations, requires little instruction, invites constant improvement, and serves as an iterative improvement to allow control and analysis [43,44]. Aligning disadvantages could include unspecified definitions leading to incorrect use [45]. Deming's cycle interacts with other quality management models by continually improving the processes required to ensure quality. In the construction industry, Deming's cycle helps build a continuous loop for controlling and improving construction processes to satisfy client and regulatory requirements [46–48]. This divides the construction processes into simple basic steps, improving processes and eliminating repeating errors.

In the era of digital transformation, Deming's cycle could be adopted to ensure that products and services adapt to market changes, improve efficiency, boost productivity, and meet the needs of customers [49]. This then ensures the quality of a construction product. Deming's cycle in QA is one of the first formalised iterative approaches to improving construction processes, and it still serves as a fundamental tool for continuous improvement to achieve quality by using the plan–do–check–act (PDCA) approach [39], which is subsequently described (Figure 2).

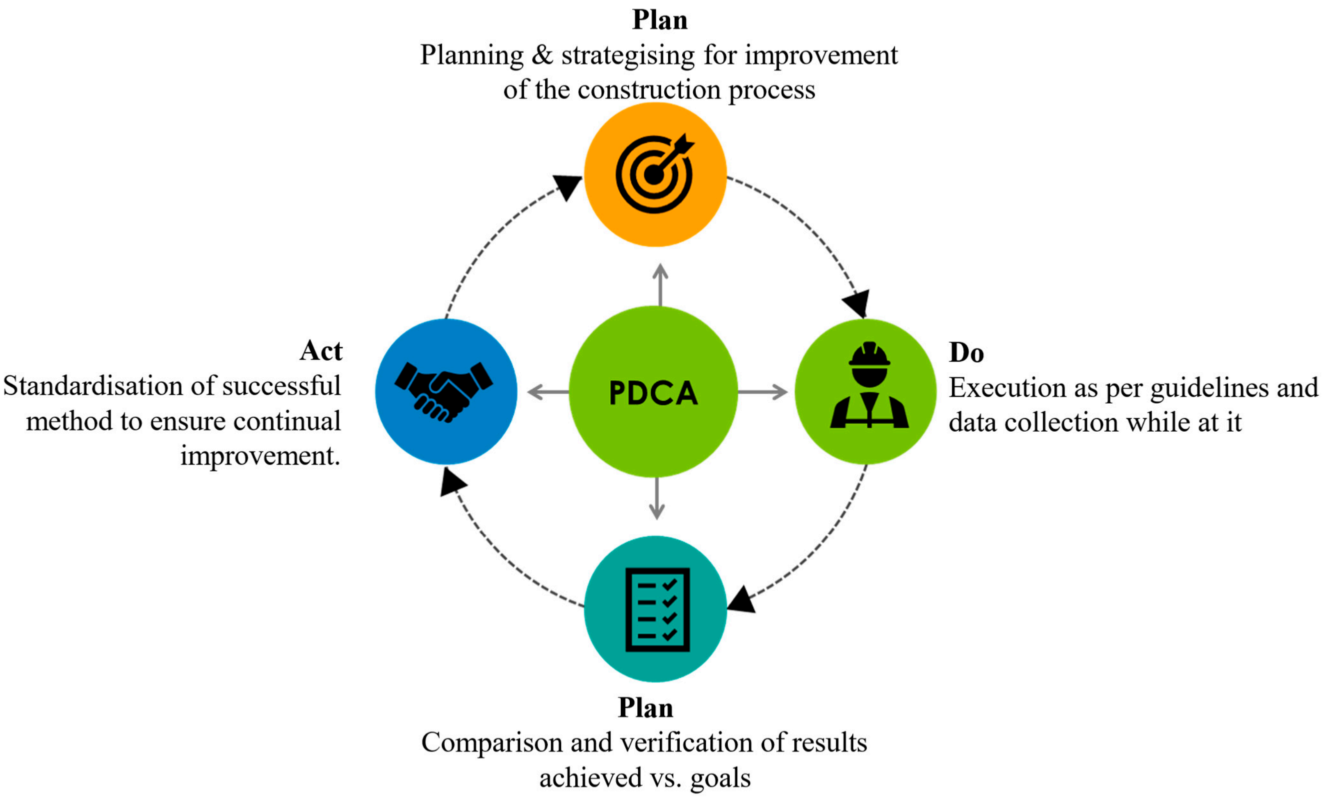

Figure 2. Conceptual framework based on Deming's cycle (PDCA cycle).

Plan, as used in Deming's cycle, involves analysing the current situation, gathering data, and developing ways to make improvements. The current state of projects or services on a project is investigated to fully understand the nature of quality needed on a project. At this phase or area, the significant question is, "What problems have you identified, and how can you best address them?" [50]. To address them, the current situation of the project is determined first. This allows quality issues to be clearly outlined to determine exactly how the quality can be achieved.

The do phase commences after planning. This is the point to execute as per guidelines and collect data while executing [50]. It requires an appointed person to execute tasks per given direction on improved processes, and effective supervision is performed to ensure that there are no deviations in what is required. Thus, actions are taken to improve QA processes by tackling the problems of quality and ensuring that services and products are executed per pre-stated quality requirements.

In the check phase, the collected results from the "do" phase are compared to the pre-stated quality requirements. A critical review is conducted to identify what worked and what went wrong in the QA process. During this phase in QA, it is important to look objectively at the plan and its implementation [50]. After the checks, the problems in quality noted to have been in the "do" phase are not to be regarded as setbacks but as an opportunity to learn from them to improve subsequent products. Thus, the "check" phase is important in identifying areas of services in QA processes where there is an opportunity for improvement.

The act phase focuses on implementing and reviewing the findings in the QA process within an organisation. This step helps fine-tune and learn from the actions that have already been taken regarding achieving quality on a project. During the "act" phase, the project and its associated services may reveal unexpected information, in which case the PDCA cycle may be repeated. It is essential to learn from the actions that led to quality failure and identify gaps for the next plan towards the quality requirement [50]. The data/information collected at this phase about service or product quality is very significant. Thus, transparency and security should be the features of such data regarding product quality after the inspection processes.

The framework demonstrates the application of digital technologies in the QA processes, highlighting the need for a systematic understanding of the application areas. Guided by this framework, four questions were established, as provided in the introduction. The first three questions align with understanding the status of the concept, identifying the technologies, and finally, examining their applications in the QA processes. The answers could inform the fourth question, which considers the limitations of the existing studies and suggests future research directions of digital technologies for QA in the construction industry.

3. Research Method

A two-step literature review approach was adopted for this study by collecting and analysing the relevant literature, following the principles of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). In construction engineering and management, this approach serves as a technique to extract and synthesise data to understand the phenomenon and proposed trends and gaps [51]. The approach is discussed, as illustrated in Figure 3, by focusing on construction QA in relation to individual digital technologies that have been applied.

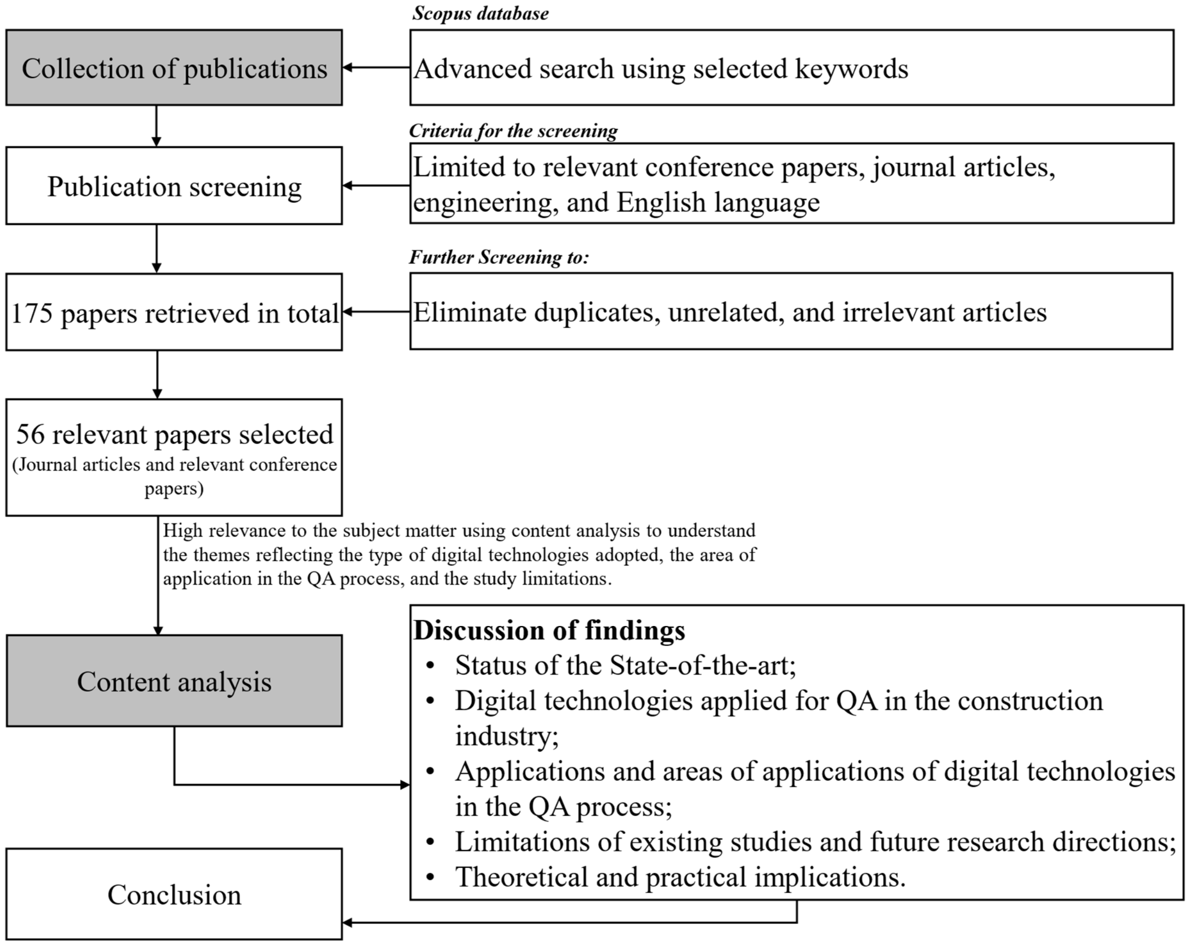

Figure 3. Study workflow.

3.1. Step 1: Publication Collection

Publications were collected from the Web of Science (WoS) and Scopus databases, facilitated by keyword search consisting of query strings such as (TITLE-ABS-KEY("digital technology" OR "Industry 4.0" OR "construction 4.0") AND TITLE-ABS-KEY("construction industry" OR "construction management" OR "construction engineering" OR "construction") AND TITLE-ABS-KEY("Quality assurance" OR "managing quality" OR "sustainable quality assurance")) AND (EXCLUDE (LANGUAGE," Chinese") OR EXCLUDE (LANGUAGE, "German") OR EXCLUDE (LANGUAGE," Russian")). This was facilitated by the Booleans "AND" and "OR". The search was limited to English, peer-reviewed journal articles, and peer-reviewed conference papers. As a result, 175 publications were retrieved, including 113 from Scopus and 62 from Web of Science (WoS), and these were noted to have been published from 2003 to 2023.

Filtering techniques were further conducted to remove irrelevant articles and duplicates by examining the articles based on the document title, abstract, keywords, introduction, methodology, and conclusion. The study also employed "inclusion and exclusion" criteria [52] following two steps. Firstly, the article must be published in a rigorously peer-reviewed reputable journal or conference. Articles published in reputable journals and conferences contribute significantly to further research and practice [53]. Second, the article must extensively cover the individual digital technologies for construction QA. The article must contain enough information to address the study's objectives. Articles that failed to meet the above-stated criteria were excluded. After meeting the criteria, 56 publications were considered adequate for this study (Supplementary Table S1), and these are highly relevant to the state-of-the-art. Moreover, none of the existing works were found to be review papers related to the research subject; thus, the study engaged only empirical papers, including journal articles and relevant conference papers.

3.2. Step 2: Content Analysis

The selected empirical articles were examined further to discuss the findings in achieving the aim of this study by conducting demographic analysis and detailed analysis, as illustrated in Supplementary Table S2. First, demographic analysis is conducted to understand the background of the selected empirical articles and their quality [54]. Lastly, a detailed analysis is conducted to understand the findings of the existing study by bearing in mind the main contents of the studies [55]. This includes the type of digital technologies adopted, the area of application in QA processes, and the current limitations of the existing studies. The detailed results of the content analysis are shown in Supplementary Table S2.

4. Findings and Discussions

4.1. Background Analysis of Relevant Literature

Detailed information was retrieved from the articles by considering the countries of the publications, the type of publications, years of publication, and the research methods adopted for the publications (Figure 4). To respond to the first question, it is essential to examine the demographic data of the articles to comprehend the status of the state-of-the-art literature.

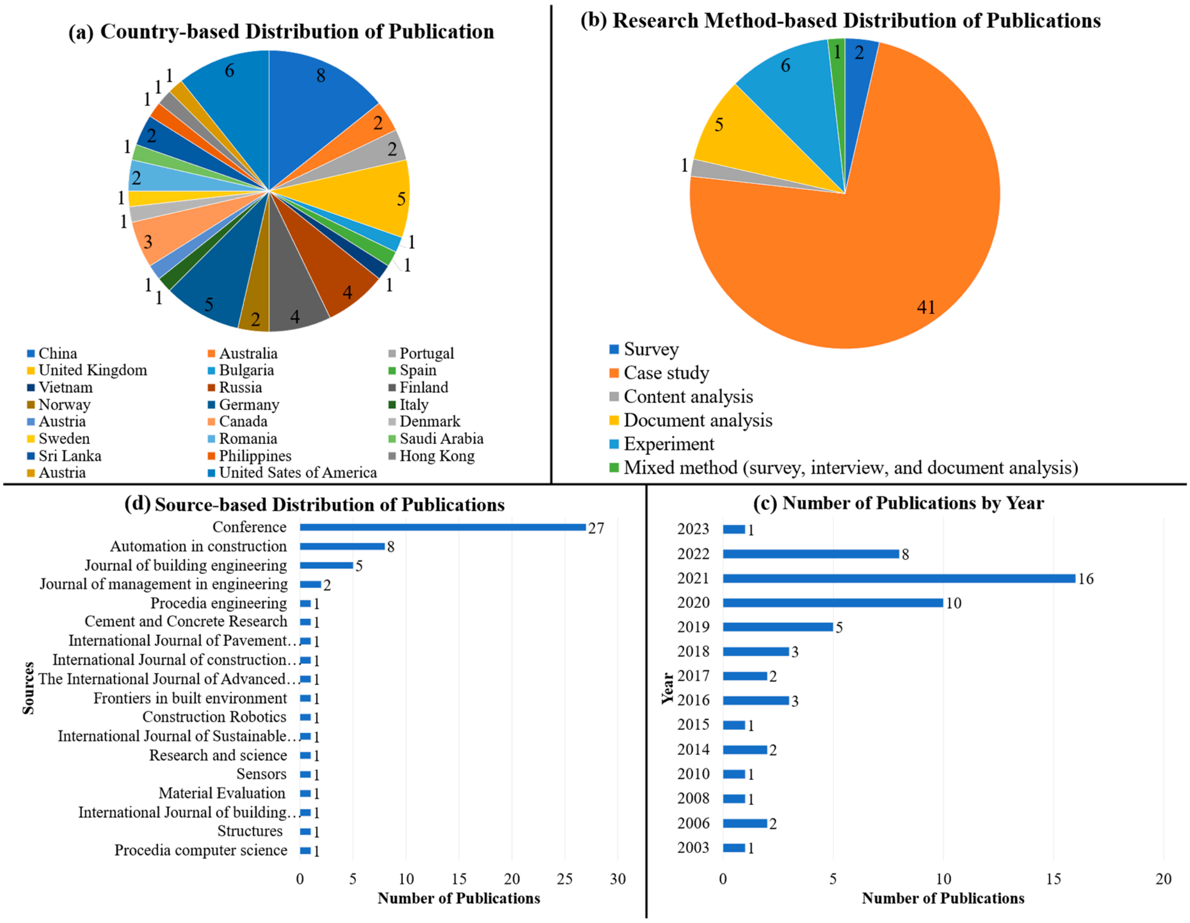

Figure 4. Background information of the selected publications.

The academic reports on integrating digital technologies for QA cut across 23 countries, adopted six different types of research methods, and were published across 18 sources (journals and conference proceedings). From the perspective of countries embarking on conducting QA in the construction industry, China seems to be the leader, followed by the United States of America, Germany, the United Kingdom, Italy, Russia, and Finland (Figure 4a). The results portrayed that the quest has been highly promoted in Asia, Europe, and America, specifically in the well-doing economies in such regions. Africa seems to be lost in the quest for QA with digital technologies, as no African article was discovered. This shows a potential gap that needs to be considered in African construction research. The results of this study can then be extended to developing economies to promote digital technologies in areas such as QA in construction to meet quality requirements.

Moreover, several research methods have been adopted by studies to understand the potential of digital technologies in influencing QA in construction (Figure 4b). Case studies have widely been used to embark on such research due to the real-time simulation and involvement of real projects. Other methods gradually gaining attention in this research domain include experiments, document analysis, and surveys. Other researchers have also adopted the mixed approach by mixing several methods, including surveys, interviews, and document analysis. Existing studies have been highly limited to the case study, making it difficult to generalise the results.

Finally, making the results of studies authentic and known is paramount. As such, journals and conferences have reported studies in this domain since 2003, with 2021 having the highest number of publications (Figure 4c). However, this field recorded no publications in 2004, 2005, 2007, 2009, and 2011–2013, thus depicting how limited this research had been. The publication numbers were seen to have risen rapidly since 2020. This may be due to the emergence of COVID-19, where integrating digital technologies into construction processes became the point of focus for academia and the industry. Meanwhile, a steady increase was noted to have occurred since 2017, except in 2022, which is anticipated to show an increase in number as well. Sixteen journals were noted to heavily promote the works of academia on reporting digital technology for effective QA (Figure 4d). Among them is Automation in Construction, having the highest publication number, followed by the Journal of Building Engineering and the Journal of Management in Engineering. Conferences across different countries have also embarked on authenticating and promoting research in this field. Conference documents were noted to be the leading source of all the sources. This may be because the face-to-face/virtual presentation nature of conference proceedings enables many scholars to present and explain their ideas on digital technologies for QA in construction to get a more robust foundation before considering journals. Reporting the findings in the form of journals and conference proceedings makes them easily accessible to practitioners and policymakers in the construction industry to inform decisions regarding conducting QA.

4.2. Digital Technologies for QA

Different digital technologies can be adopted for QA in the construction industry, as illustrated by the study results in Table 1. From Table 1, digital technologies can be integrated into the QA processes to improve quality decision-making, as most technologies adopted are noted to be decision-oriented. The study revealed that BIM-based communication technologies are prevalently adopted among all individual technologies to ensure effective collaboration among relevant stakeholders throughout the QA process to achieve quality. It can also be highly noticed that data collection technologies could be integrated into collaborative technologies to improve the QA processes based on efficient decision-making using AI, ML, etc. Existing studies have been highly limited to the BIM technology application, focusing less on integrating other technologies.

Digital technologies for QA in the construction industry can be divided into four categories: data collection technologies, decision-oriented technologies, collaborative technologies, and transparency and security-related technologies. This is based on the functionality of the technologies as applied in the studies. However, it is worth noting that some of the technologies can fall within more than one category, including VR/AR, IoT, digital twins, etc. These are discussed further to understand their relation to achieving QA, answering the second question.

Table 1. Category of digital technologies adopted for QA based on functionality.

Category	Technologies
Data collection	• Terrestrial laser scanning • Mobile digital technology • Three-dimensional modeller • IoT • VR/AR • Radiofrequency identification system • Cyber-physical system • Drone aerial photography • Indoor positioning system • Multi-rotor drones • Thermal Camera • Geodetic surveying technology • Digital inspection test tool • Robotic system • The automated vision-based online inspection system • Intelligent ultra-wide caster • Condition-based monitoring system
Decision-oriented	• Real-time performance data system • Point cloud of as-built work • Big data • Photogrammetric vision • Barcode • Fog and cloud computing • C-Suit level • Digital twin technology • 2D geological model • AI • ML/Neural network/Deep learning
Collaborative	• BIM-based Communication technology
Transparency and security-related	• Blockchain and other security systems

Note: Detailed table showing the individual digital technologies with the number of sources/references is shown in Supplementary Table S2.

4.2.1. Data Collection Technologies

Data collection is significant throughout the QA process, as its interpretation helps understand if a product or service meets the quality. Previously, data was collected manually during QA in the construction via in-person observation and documentation on-site [56]. This manual process becomes laborious and time-consuming, especially when the construction project is complex and requires a lot of documentation and observations. This sometimes makes the QA processes efficient towards achieving the project quality requirements.

The evolution of Industry 4.0 and its promotion in the construction industry has a higher chance of facilitating and improving the QA processes towards achieving project quality. Integrating digital technologies into QA practices/processes has made data collection efficient and retrieved inaccessible data from critical parts of construction projects [19,57–59]. For instance, VR/AR adoption for QA can ease the work of quality auditors/engineers by scanning through an ongoing building project to collect data from a single location by reducing the number of times to be on construction sites [60]. Other digital technologies can improve the QA practices and processes to collect quality data for interpretation and audit project quality on quality requirements. These include technologies such as laser scanning and indoor positioning systems [18,19,29,61].

4.2.2. Decision-Oriented Technologies

Decision-making regarding the project quality is critical in QA processes after data collection [62]. Data collected during the QA processes are further examined to understand the level of quality an ongoing construction project has attained. In the case of a complex project, a huge amount of data is collected, thus becoming tedious and laborious to make interpretations manually.

The Industry 4.0 evolution has the propensity to improve and facilitate the QA processes towards efficient decision-making by incorporating digital technologies. For instance, big data may be a technological concept referring to the large amount of data relating to the quality of a complex construction project. This becomes challenging to interpret manually for efficient decision-making. Hence, artificial intelligence/machine learning (AI/ML) can be integrated to make interpretations from a large amount of data [58,63]. Moreover, fog/cloud computing can also store a large amount of data in the cloud, allowing further interpretations of data by AI/ML. Digital technologies can also be applied to small and medium projects to ensure efficient decision-making regarding the QA processes. Decision-oriented technologies include but are not limited to digital twin technology, photogrammetric vision, and computer vision [26,58,64].

4.2.3. Collaborative Technologies

Collaboration is significant in the QA processes in the construction industry due to the different stakeholders/parties involved in producing products to satisfy the client's needs. Collaboration may also ensure that construction services are following all contractual codes, specifications, and standards or government regulations. As such, data/information related to the project are shared among the stakeholders to ensure the product meets the pre-stated quality requirements [65]. Thus, an effective collaboration system may be established to allow active and efficient interactivity among the parties or stakeholders to make sure information flows from one party to the other, as well as parties are aware of what other parties are doing on the project. This interactivity may involve the client, designer/architect, quality engineer/auditor, authorised agency, etc.

Industry 4.0 has positioned collaboration among the parties to an efficient level because of the integration of digital technologies. Different perspectives of stakeholders may require individual digital technologies that can smoothly promote the sharing of information towards project execution to satisfy user and statutory requirements [65,66]. Digital technologies can enhance QA in construction by improving and facilitating collaboration through effective communication and sharing of information regarding the quality of a project [67]. Collaboration is one of the biggest benefits of BIM as it allows engineers to share relevant and accurate information with different stakeholders, such as designers, managers, etc. [68]. BIM technology in QA creates a unified data standard that makes it easier to transfer data to different stages of project development and guarantees accurate and up-to-date data for managing quality [26,27]. The study finally revealed that, though data collection technologies as a category have been largely adopted in the QA processes, the BIM as an individual technology has been widely integrated to ensure effective collaboration among the relevant stakeholders with diverse perspectives regarding the project design, construction, and management (Figure 5a) [19,30].

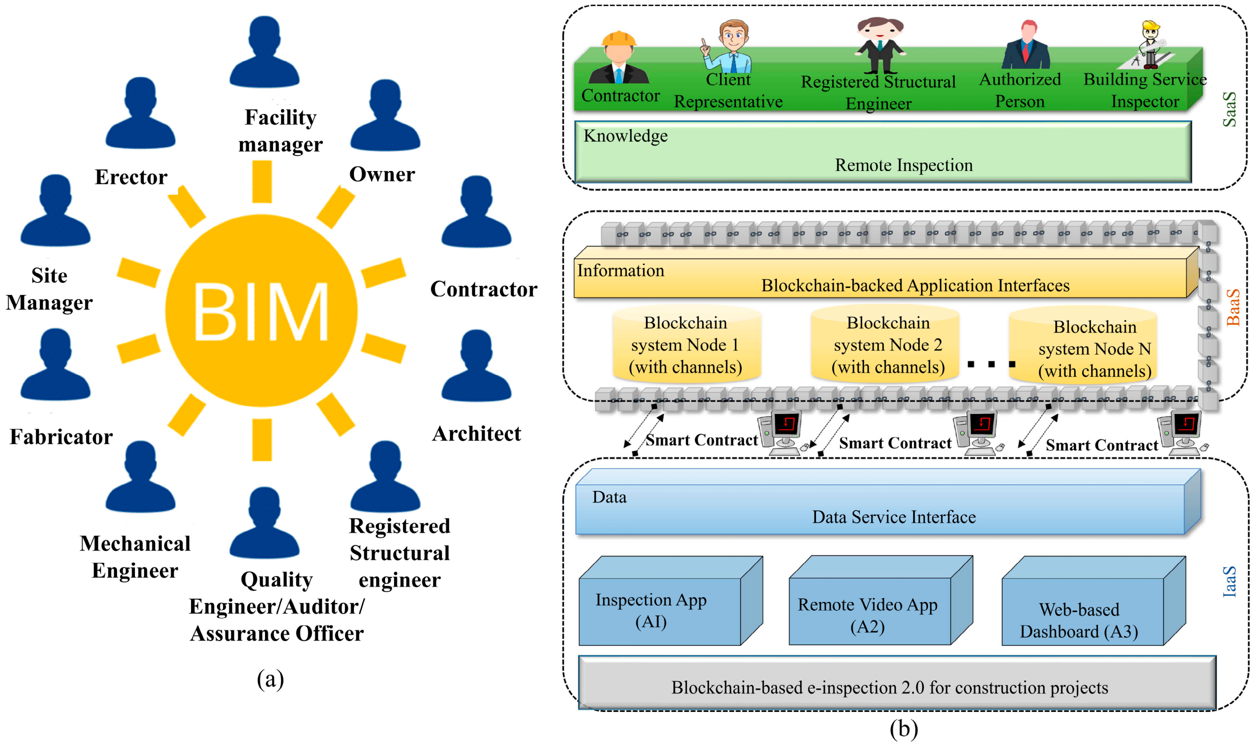

Figure 5. (**a**) Illustration of BIM-based collaboration among stakeholders in the QA process; (**b**) Illustration of blockchain-based inspection on construction site (Adapted with permission from [69]).

4.2.4. Transparency and Security-Related Technologies

Transparency and security are very important when information/data are transferred between parties. Data relating to quality checks and inspections on construction sites are very important and, thus, must not be altered. Getting unaltered data on the quality of products or services can help make an effective decision and ensure significant improvement [33]. To ensure the transparency of collected data on the services and products during QA, security is thus important.

With the emergence of digital technologies, the data flow can be protected to ensure data is secured and transparent. For instance, blockchain technology is integrated into the QA processes/practices to provide a disruptive new method of conducting transactions over the internet by enabling encrypted, distributed, and secure logging of digital transactions [70]. This allows users to exchange sensitive data without the need for brokers and other party mediators, as well as ensuring data transparency among related parties or stakeholders during the quality inspection process (Figure 5b) [69]. However, the blockchain network system is dysfunctional without technologies for collecting decision-making data, including collaboration, etc. Together with BIM, blockchain can create a single source of truth for all aspects relating to the quality of a construction project. Such a model can become the trusted digital platform in QA processes to ensure that the construction project meets the client's needs and other quality requirements. Notably, transparency and security-related technologies can be incorporated into the different categories of technologies, including data collection technologies, decision-oriented technologies, and collaborative technologies for QA systems. Existing studies have limited the transparency and security-related technologies to mainly blockchain [33,71].

4.3. Areas of Application

From the perspective of Deming's cycle, the applications of digital technologies for adequate QA are evaluated and discussed to understand how they improve the QA processes, thus responding to the third question. Evaluating the applications based on Deming's cycle denoted that those various digital technologies have been highly adopted at the "do" phase to improve the quality management process during construction towards achieving pre-stated quality requirements. This includes mostly collaborative technologies, consisting of BIM technologies. Table 2 shows the applications of digital technologies for QA along with the limitations of the existing studies. Table 2 also shows the results after evaluating the applications from the perspective of Deming's cycle.

Table 2. Applications areas of digital technologies for QA.

Deming's Cycle Phases	Application	Technologies
Plan	• Carrying out safety tests and evaluation; • Cost and time predictability.	• Drone aerial photography; Terrestrial laser scanning; BIM; • Three-dimensional modeller.
Do	• Improving management processes at the construction/production phase; • Improving maintenance management; • Control tasks of the entire construction production process; • Reduction of errors and defects; • Reduction of material wastes; • Product customisation and adaptability; • Achieve and control production quality by checking the accuracy; • Screw-fastening operations in light-gauge steel frame manufacturing of quality modular construction projects.	• Photogrammetric vision; • Barcode; • Condition-based monitoring system; • 2D geological models; • Digital inspection test tool; • Mobile digital technology; • Radiofrequency identification system; • VR/AR; • Point cloud of as-built work; • IoT; • Intelligent ultra-wide caster; • Blockchain and other security systems; • Robotic system; • Geodetic surveying technology; • Real-time performance data system; • Blockchain and other security systems; • Thermal Camera; • Three-dimensional modeller; • The automated vision-based online inspection system.
Check	• Checking the geometric quality of buildings; • Checking the strength of buildings; • Automatically Identifying and tracking the pipes of an infrastructure; • Quality checks and supervision; • Quality monitoring.	• Terrestrial laser scanning; • Thermal Camera; • Three-dimensional modeller; • AI; • Fog and cloud computing; • Multi-rotor drones; • Digital twin technology; • ML/Neural network/Deep learning; • IoT; • VR/AR.
Act	• Ensure construction quality management is more effective and collaborative; • Ensure data transparency and protection during data collection on the project.	• Terrestrial laser scanning; • Indoor positioning system; • BIM-based Communication technology; • Blockchain and other security systems.

Note: Detailed table showing the application of the individual digital technologies with the number of sources/references is shown in Supplementary Table S2.

4.3.1. Plan

During the "plan" phase, digital technologies can be embedded to make accurate predictions to inform decisions on project quality [72]. This involves examining the current construction project situation to ensure that ongoing projects meet the pre-stated requirements. Applications of digital technologies, such as AI, VR/VAR, and other simulation technologies that have been applied at the planning phase, include carrying out safety tests and the evaluation of projects and predicting the time and cost impacts on the quality of a project [18,73,74]. Adopting digital technologies helps to easily clarify the quality problems that need to be dealt with in the QA processes and practices so that the project can meet the pre-stated requirements. Thus, digital technologies are adopted to evaluate the state of quality during QA in construction projects to explore the impact of the errors made and address them with the appropriate measures before the final product is completed for client usage. Since PDCA is an iterative approach, services and ongoing projects are continuously planned and evaluated to identify the right quality problems to meet project quality requirements.

4.3.2. Do

In the "do" phase, QA processes are improved by addressing quality issues and ensuring that services and products adhere to pre-stated quality requirements. The emergence of digital technology and its promotion in the construction industry has the propensity to facilitate and improve the construction processes and operations towards quality. In the studies, the areas of digital technology application in QA processes in the "do" phase have been limited to improving maintenance management, construction/production process management, and operations [20,27,32]. Furthermore, digital technologies, such as AI, computer vision, photogrammetric vision, thermal cameras, etc., can be integrated into QA processes to ensure a reduction in errors and defects and check accuracy during the execution of projects [75–77]. Thus, integrating digital technologies into QA in the "do" phase improves the processes to ensure that the right services are performed in delivering the required project to meet client needs and standards, codes, and regulatory requirements.

4.3.3. Check

The "check" phase is important in identifying areas of services in QA processes where there is an opportunity for improvement. Promoting digital technologies can improve the QA processes regarding the "check" phase. Data collected with the help of VA/AR, cameras, laser scanning, etc., are sorted, organised, and analysed to inform decisions on the quality of construction projects and services. Digital technologies are introduced to find any point of correction in a previously known impeccable plan. Comparing achieved results on quality to outlined expectations is challenging and laborious in complex projects [78]. Digital technologies, such as AI, computer vision, and simulation technologies, can be implemented to facilitate the QA at the "check" phase. For instance, digital technologies such as digital twin technology platforms embedded with AI are adopted to check the geometric quality of buildings, check the strength of buildings, identify and track pipes of infrastructure, and monitor the quality [29,30,64]. Thus, adequate checking can be conducted if the appropriate digital technologies are integrated into QA during the "check" phase of Deming's cycle in QA.

4.3.4. Act

In the "act" phase, collected data on the quality of a project can be protected against third-party interference and ensure a single source of truth with the integration of digital technologies [79]. For instance, blockchain technology can ensure data transparency and security during data collection on the project regarding quality auditing and inspection [33,71]. In the "act" phase, blockchain technology ensures a single source of truth during data collection. Thus, integrating digital technology, such as blockchain with BIM in this phase guarantees the effectiveness of QA processes in construction through effective collaboration among relevant stakeholders [19].

4.4. Conceptual Framework

Based on the findings, this study proposes a conceptual framework to assist with the understanding of integrating digital technologies into QA in the construction industry (Figure 6). The framework consists of digital technology categories (top stream) and the applications evaluated from the perspective of Deming's cycle in QA (bottom stream). The two streams were critically discussed in Sections 4.2 and 4.3.

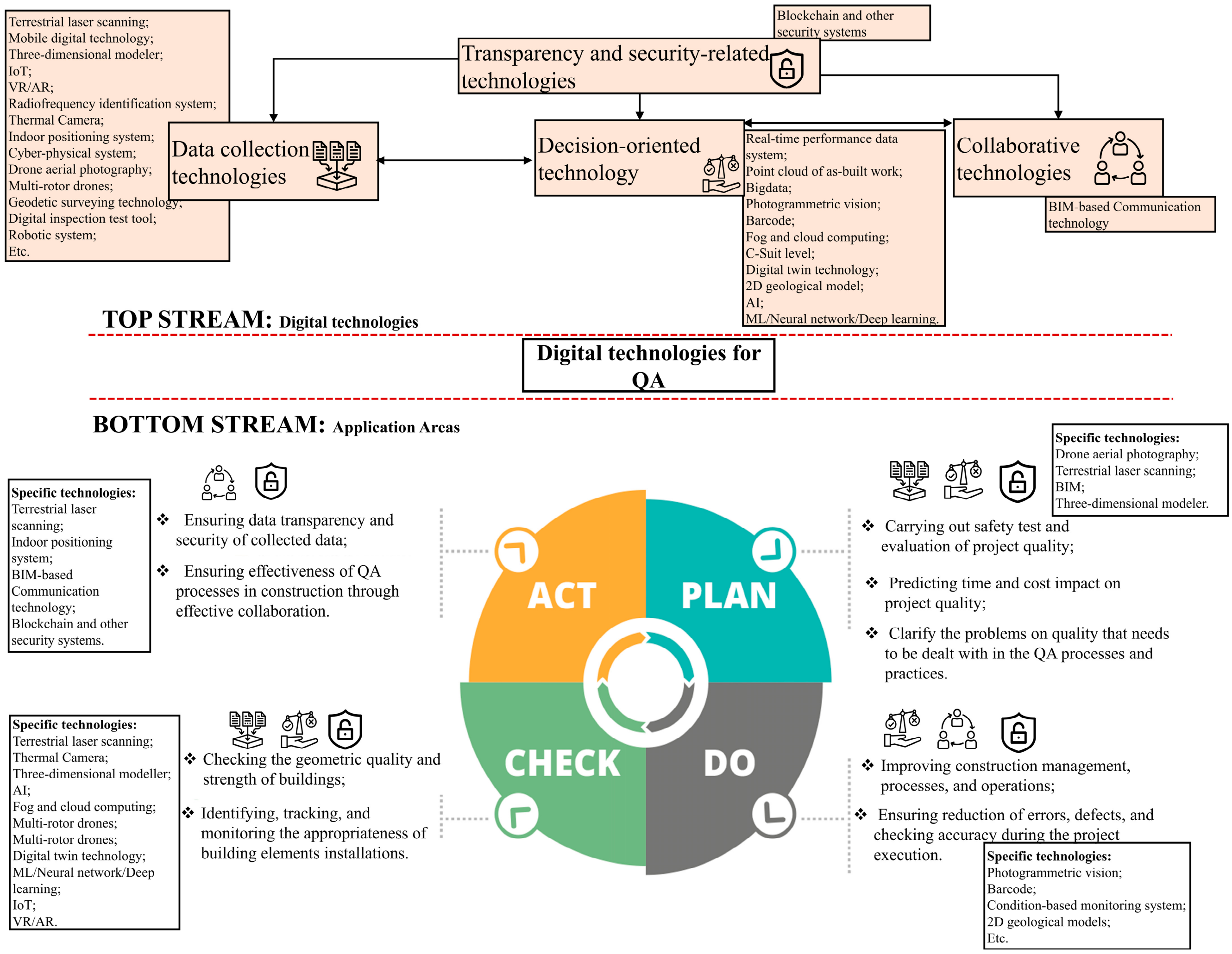

Figure 6. Conceptual framework on the application of digital technologies for QA in the construction industry.

This section discusses the conceptual framework generated from combining the two streams. Quality is a desirable feature of construction projects, and its attainment is premised on the effective management of construction processes, maintenance, and operations [10,11]. In the evolution of Industry 4.0, the construction process, production, and operation delivery have been augmented with digital technologies. This facilitates and improves activities related to ensuring the quality of construction projects.

From Figure 6, the top stream shows the digital technologies adopted in construction for QA, and these are categorised into the following: data collection technologies, decision-oriented technologies, collaborative technologies, and transparency and security-related technologies. The digital technologies adopted for QA are significant as they assist professionals in understanding the quality of services and ongoing products/projects with the right data and correct interpretation [23,28]. For instance, BIM, as a collaborative technology, allows stakeholders to share relevant and accurate information on the quality of a project as well as enhance interactions. This may exist between the designers, managers, quality engineers/auditors/assurance officers, clients, etc. Integrating two or more digital technologies improves the efficiency of a system depending on the purpose [80]. This is affirmed by this study as the conceptual framework (Figure 6) shows that certain categories of technologies can be embedded with other technologies to ensure an efficient system to assess the quality of a construction product effectively [69]. For example, BIM, a collaborative technology, is integrated with cloud computing and AI to store collected data and make decisions that can inform quality. IoT, BIM, cloud computing, and several other digital technologies can also be integrated [69]. This also includes the transparency and security-related technologies that can be embedded in all the categories to protect collected data. For instance, integrating blockchain technology into the BIM platform can guarantee a single source of truth on the data transactions among all the relevant stakeholders of a project [69,81]. Thus, the top stream of the conceptual framework highlights the categories of digital technologies and their interrelations to ensure that the right data on quality are collected, protected, secured, and shared among the relevant stakeholders through the QA processes to achieve the best quality project.

The bottom stream of the conceptual framework highlights the application areas of digital technology's adoption for QA with the category of technologies adopted. From the perspective of Deming's cycle in QA, digital technologies are adopted significantly across the PDCA stages, improving the QA processes and practices through an iterative process (Figure 6). At the "plan" phase, digital technologies can be deployed in the QA processes to make predictions to understand the impact of time and cost on quality performance [34]. Primarily, digital technologies are implemented in this phase to clarify quality problems that need to be dealt with. This may include data collection technologies and decision-oriented technologies. Transparency and security-related technologies may also be involved to ensure data protection at this phase. At the "do phase," the implementation phase, in assuring quality, digital technologies are adopted to improve the construction processes, production, and operations [50]. In doing so, errors and defects are reduced, and service accuracy is checked during project execution. The category of data may include decision-oriented technologies and collaborative technologies. Transparency and security-related technologies may be involved to ensure a single source of truth among relevant stakeholders during collaboration. Digital technologies are deployed in the "check" phase to assist in identifying, tracking, and monitoring the appropriateness of construction products compared to expected products [50,69]. This extends to the checking of geometric quality and strength of buildings. The categories of technologies may include data collection technologies and decision-oriented technologies. Data transparency and security-related technologies may be adopted to ensure the collected data are safe. At the "act" phase, digital technologies are deployed to ensure that data collected are transparent and secured. Moreover, digital technologies ensure the effectiveness of QA processes in construction by guaranteeing effective collaboration among relevant stakeholders [33,69]. This may mainly involve collaborative technologies and "transparency and security-related technologies", including BIM, blockchain, etc. Throughout the four phases, the transparency and security-related technologies are very significant, as they ensure the data collection is safe in forming decisions regarding project quality [81]. Thus, the bottom stream of the conceptual framework reveals how QA can be achieved if the appropriate technologies are integrated into the QA processes and practices based on the perspective of Deming's cycle.

5. Limitations and Future Research

This section seeks to answer the fourth question by synthesising the findings from the first three questions of the study.

5.1. Limitations of Existing Studies

The study discovered 56 empirical studies conducted, denoting limited research in the field. Reviewing the selected existing studies showed a few strengths and weaknesses. The strengths of the studies were noted as the applications that have been robustly discussed in Section 4 towards a conceptual framework for understanding digital technologies for QA in the construction industry. Thus, the strength lies in the findings of the existing studies and the ability to report based on the research methods adopted. However, the limitations of the existing studies were examined, and the outcomes may inform future research directions.

Among the selected studies, limitations were found to exist in two main forms: technology-oriented and methodology-oriented (Table 3). Moreover, individual limitations were evaluated from the perspective of Deming's cycle in QA (Table 3). Upon the evaluation, the concern of the narrowness of technology readiness was noted in several studies, and this cut across Deming's cycle. The two main forms of limitations discovered are further discussed.

Table 3. Limitations of current studies across Deming's cycle in QA.

Limitations	Deming's Cycle			
	Plan	Do	Check	Act
Technology-oriented				
• The narrowness of technology readiness	✓	✓	✓	✓
• Lack of clear push for digital technologies for QA	✓			
Methodology-oriented				
• Inadequate integration of technologies	✓	✓		✓
• Lack of efficient methodology conceptualisation	✓		✓	
• Lack of validation and testing on accuracy and applicability	✓			
• Lack of clarity on the model's efficiency			✓	
• Inefficient automatic association with construction schedules and inspector assignment with the digital system				✓
• Lack of customisation of check items and criteria from the standard for different application scenarios				✓
• High technicalities				✓

✓ Signifies the area of limitation in Deming's cycle. Note: Detailed table showing the limitations aligned with the sources/references and the applications are shown in Supplementary Table S2.

5.1.1. Technology-Oriented Limitation

The existing studies are limited by the narrowness of technology readiness and the lack of a clear push for digital technologies. A low level of technology maturity is illustrated in the studies' propensity to properly embrace and apply new technologies to accomplish the goals of ensuring QA in a construction project. The existing studies showed inconsistencies and a lack of uniform discussion of the technical maturity across different types of digital technologies. This results in a lack of confidence in the digital technologies in making QA adequate and the lack of top management commitment to push for technologies in the QA process. Moreover, the evaluation of the limitations denoted that, across Deming's cycle in QA, reports on the technicalities of the digital technologies for QA but hardly emphasises the effective ways for pushing for the technologies to entice clients and other relevant stakeholders to embrace them. Thus, this study recommends that future studies adopt effective strategies to promote and push for the uptake of digital technologies for QA whilst reporting on the technologies' technicalities. This may influence decisions to push the top management in organisations to support digital technology integration into QA processes in the construction industry, hence improving the technology readiness among all stakeholders. Furthermore, specific criteria can be used to assess the readiness level by checking the level of maturity, awareness, and ability to use individual technologies. These criteria may help to understand the level of readiness of an organisation towards digital technologies for QA in construction.

5.1.2. Methodology-Oriented Limitation

The existing studies were also noted to be limited by methodology, and these exist in two forms. First, some limitations resulted from the research methods adopted for the studies (Table 4). Research methods such as case studies have been heavily adopted in the research subject because of the ability to generate an in-depth, multi-faceted understanding of a complex issue in its real-life context. Nonetheless, existing studies that adopted case studies lack scientific rigour and provide little basis for generalising results. Thus, as many studies were noted to have adopted case studies, the existing results may be difficult to generalise with respect to ensuring quality. Few research methods have been adopted aside from the case studies, and their strengths and weaknesses are shown in Table 4. Thus, the study recommends future studies adopt advanced research methods to help improve the generalisation of research results so that efficient decisions can be made to inform QA processes/practices. Second, the other limitation relates to a methodology that lies in the nature of the study, i.e., method-based research to achieve great efficiency in applying technology for QA. For instance, studies were noted to have shown inadequate integration of digital technologies into QA processes. This may result from a lack of efficient methodology conceptualisation, lack of validation and testing on accuracy and applicability, lack of clarity in the model's efficiency, high technicalities, etc. Thus, the study recommends future studies adopt a robust methodology to achieve an efficient methodological integration of digital technologies for QA in construction.

Table 4. Limitations of existing studies based on the research method adopted.

Adopted Research Methods	Strength	Weakness
Case study	• In-depth insight and multi-faceted understanding.	• Lack of scientific rigour; • Lack of result generalisation.
Experiment	• Clear conclusions and specific.	• Depends on what many see as an "artificial" environment (low realism).
Survey	• Convenient data gathering; • Not Ideal for Controversial Issues.	• Inflexibility and issues with depth.
Content analysis	• Yields rich insights; • Easily replicable and affordable.	• High level of subjective interpretation; • Time-consuming and disregards context.
Document analysis	• Does not disturb the operational sequence or only minimally.	• Information overload; • Biased selectivity.
Mixed method (survey, interview, and document analysis)	• Better understanding of the problem; • Yield more complete evidence.	• More complex; • Require more expertise to collect and analyse data.

Note: Detailed table showing the limitations aligned with the sources/references and the applications are shown in Supplementary Table S2.

5.2. Future Research Direction

Based on the review findings, several research gaps have been identified, and future research directions are proposed and discussed in the following subsections. The suggested areas are based on examining the future works proposed by previous papers and on the untapped potential for digital technologies within the context of QA that has been identified from the analyses (Figure 7).

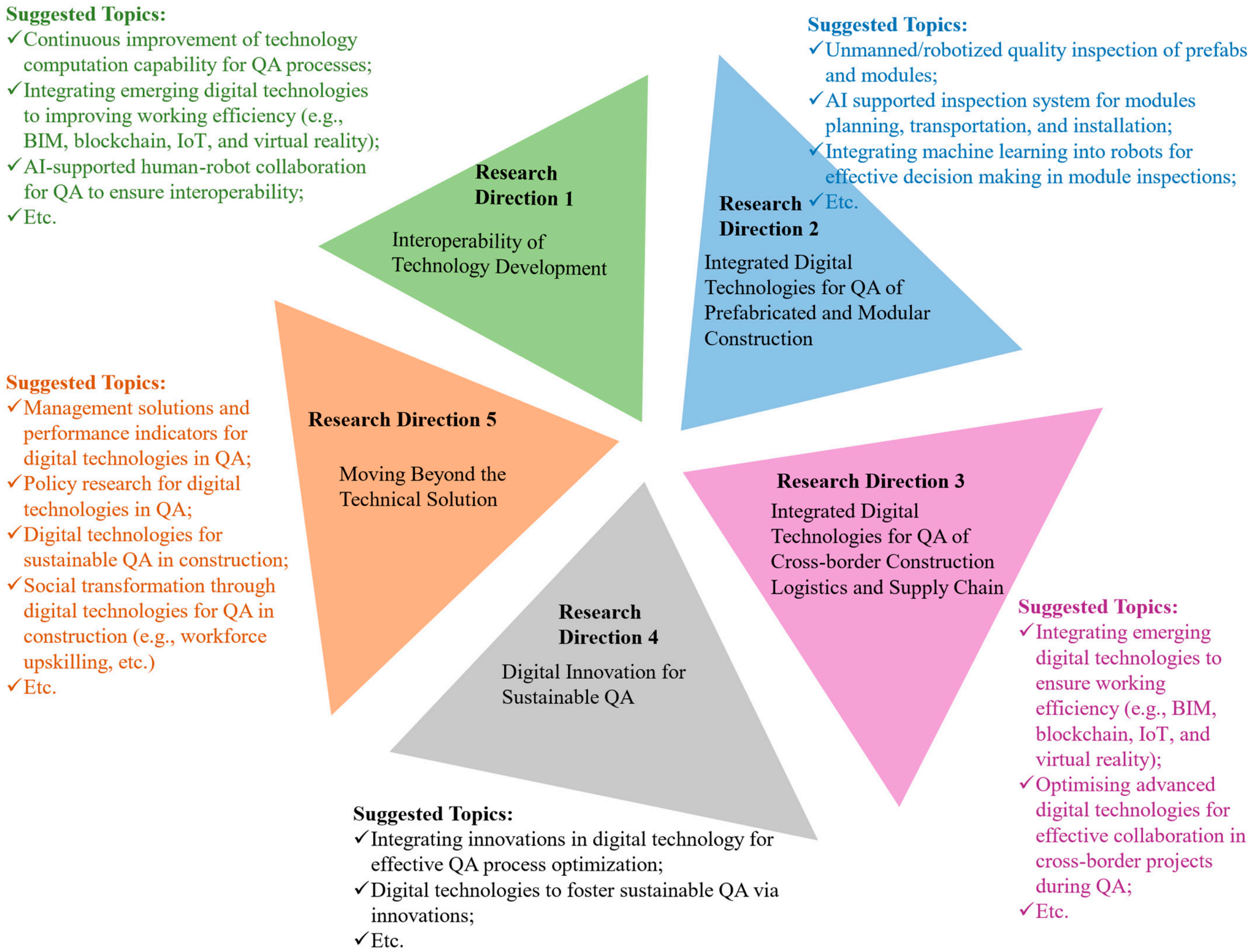

Figure 7. Future research directions of digital technologies for QA in construction and suggested topics.

5.2.1. Direction 1: Interoperability of Technology Development

Digital technology for QA in the construction industry can be regarded as highly interdisciplinary, integrating several disciplines involving science, engineering, and management. Most previous research focused on applying digital technology to solve specific problems regarding quality in construction and the efficacy of technology through QA processes, but few have focused on integrating digital technologies to ensure higher efficacy [19,33]. More interdisciplinary efforts are required to assist in solving the rising problem of technology integration for QA. From examining the existing applications, digital technology integration should be further explored with considerations from the broader context and other disciplines, like data transparency and security, data storage and accessibility, and technology interoperability [82]. For instance, cases of blockchain technology have illustrated the potential of ensuring transparency of data management towards trustworthiness, which can enhance the decision-making on quality goals using BIM and IoT [81,83]. Hence, an important future direction for research relates to the interoperability of technology development to achieve an efficient QA leveraging the potentials of individual digital technologies and how they can be integrated.

5.2.2. Direction 2: Integrated Digital Technologies for QA of Prefabricated and Modular Construction

Prefabricated and modular construction has been regarded as an essential effort for wider construction, and its ability to satisfy the client is premised on the quality services applied during production and installation. To ensure quality, Martinez et al. [32] pointed out the application of an automated vision-based online inspection system to screw-fasten operations in light gauge steel frame manufacturing for a quality modular construction project. Blockchain technology is also integrated into the QA process of modular construction to ensure transparency and security of inspection data shared among relevant stakeholders [33]. Reviewing existing literature denoted a few research foci on applying digital technologies for QA in modular construction. More efforts are thus required to apply digital technologies for QA in the context of delivering prefabrication and modular construction projects. Therefore, combining the findings of this study, a promising future research direction could be integrating digital technologies into QA processes of prefabrication and modular construction.

5.2.3. Direction 3: Integrated Digital Technologies for QA of Cross-border Construction Logistics and Supply Chain

Conducting QA of cross-border construction logistics and supply chain embraces organisational resources, structure, and procedures [10], and this has been the responsibility of the contractors, consultants, designers, quality officers, and government-authorised agencies. This denotes an effective collaboration among these parties across borders/regions/countries if the quality of a project is a goal. The potential of digital technologies in the context of QA of cross-border construction logistics and supply chains has not been sufficiently tapped, especially in a pandemic era like COVID-19, where there is a restriction in movement from one region to another. Reviewing the literature denoted insufficient studies conducted in this domain [33]; hence, more efforts are required to investigate digital technologies' potential for QA in cross-border construction logistics and supply chains. Cross-border construction logistics and supply chains are gaining popularity with their capability to connect regions and exchange services to strengthen bonds between regions/countries [84]. Hence, ensuring the delivery of quality cross-border projects is very important. By fusing the findings of this review, promising research might be conducted to integrate digital technologies into the QA processes of cross-border construction logistics and supply chains.

5.2.4. Direction 4: Digital Innovation for Sustainable QA

Sustainable quality is a recognisable feature of construction projects premised on sustainable and QA practices, and this can be achieved through innovations out of digital technology integration. Once the QA processes are digital, the evaluation of the data collected can be conducted without any cost whilst enhancing ground-breaking insight into the data. This denotes an effective QA process optimisation, digitally innovating to ensure the project meets the pre-stated requirements. The potential of digital technologies for QA is more recognisable if innovation is integrated into the QA processes. Beyond quality management, digital technologies can offer benefits to achieving sustainability, such as reducing energy use throughout the construction process due to streamlined tasks, improved waste reduction due to better tracking, and increased efficiency through new features and collaboration tools available with digital technologies. This review denoted some applications of digital technologies for QA but was not exhaustive. However, more potential can be recognised if innovations are integrated into the use of digital technologies for QA. Hence, promising research might be to associate innovation with digital technology to discover the untapped potentials of digital technologies for QA in construction.

5.2.5. Direction 5: Moving beyond the Technical Solution

Social issues, management, and regulations concerns for technology transfer in digital technologies need to be considered aside from the technical issues [85]. Despite the rising general discussions on the non-technical issues of digital technologies [86,87], there is limited research regarding how digital technologies should be managed, assessed, deployed, and regulated from a socio-technical system perspective [88]. Integrating digital technologies into QA could disrupt other systems, including the labour structure, stakeholder relations, business models, and the environment [38,89–91]. Therefore, more studies are needed on these surrounding technological concerns to support real-world cases of applying digital technology for QA in the construction industry, considering the social implications, management, and regulatory issues.

5.3. Theoretical and Practical Implications

Theoretically, this study contributes significantly to the knowledge of digital technology applications for QA in construction by synthesising previous studies and offering insights into future discoveries in this promising field. This paper demonstrates the usefulness of Deming's cycle in QA in understanding and examining the application areas of digital technologies for QA in the construction industry. The findings should enrich research interest and act as a catalyst to drive practice and enhance industry support for deeper and cutting-edge research into this field.

Practically, the findings of this study, especially the conceptual framework, create awareness among related industry players on the practical adoption and implementation of digital technologies for construction QA, as well as informing policymaking, for instance, planning and strategising the adoption and implementation of digital technologies throughout the QA process by following statutory and clients' requirements on a project. This may enhance effective collaboration among related stakeholders to arrive at informed decisions towards project execution, which would meet statutory and client requirements. The finding may also inform policymaking on the applications of individual digital technologies to enhance the QA process, as well as their relevance to the process.

6. Conclusions

The study organised and conducted a systematic evaluation and synthesis of the individual literature on digital technologies for QA in the construction industry, which is a gap in the subject area (literature) despite the growing rich attention and its fragmented nature in the literature. This area is given limited attention in research. Meanwhile, if conducted, it could provide a solid foundation for future research. The analysis involves a review of relevant papers published from 2003 to 2023, which were selected from the WoS and Scopus databases. The review was guided by Deming's cycle in QA, which evaluated the applications of digital technologies for QA by considering four interrelated phases: plan, do, check, and act. The key findings are provided next.

The first research question is answered by an in-depth analysis of the detailed demographic data about the selected relevant articles. The findings show a steady increase in research of digital technology for QA in construction since 2017, except for 2022, which is anticipated to show an increase in number as well. This cuts across 23 countries with six different research methods published across 18 different publication sources. Moreover, China seems to be the leading country embarking on research integrating various digital technologies for QA, followed by the United States of America, Germany, the United Kingdom, Italy, Russia, and Finland. Among the several research methods adopted in the literature, the case study has been adopted widely because of real-time simulation and the involvement of real projects. In making the results authentic and widely known to influence decision-making in the industry, both conference proceedings and journals have actively been engaged.

Analysing the digital technologies adopted by the existing studies answered the second question by revealing that, among all individual technologies, BIM-based communication technologies are prevalently adopted to ensure effective collaboration among relevant stakeholders throughout the QA process to achieve quality. The individual digital technologies applied for QA in construction could be consolidated into four main groups based on the functionality of the technologies: data collection technologies, decision-oriented technologies, collaborative technologies, and transparency and security-related technologies. Furthermore, data collection technologies could be integrated into collaborative technologies to improve the QA processes based on efficient decision-making using AI and ML.

In answering the third question, the application areas were further synthesised throughout different phases guided by Deming's cycle in QA: plan, do, check, and act. This study shows that various digital technologies have been highly adopted at the "do" phase to improve the quality management process during construction towards achieving pre-stated quality requirements. This includes mostly collaborative technologies, consisting of BIM technologies. The paper concluded that digital technologies have considerable potential for QA by enhancing the processes, but previous studies were limited, and more efforts are needed.

The fourth research question was answered by distilling the insights from and synthesising the previous studies and recommending five future research directions on digital technologies for QA in construction: (1) interoperability of technology development, (2) integrated digital technologies for QA of prefabricated and modular construction, (3) integrated digital technologies for QA of cross-border construction logistics and supply chain, (4) digital innovation for sustainable QA, and (5) moving beyond the technical solution. Before revealing the future research directions, the study concluded that there are various outcomes of a few studies depicting the application of digital technologies for QA in the construction industry, but these have been limited, requiring more efforts in the field. Hence, together, the four directions provide a plausible future for QA in construction adopting digital technology.

Despite the theoretical and practical contribution of this study, some limitations must be considered when applying the findings of the study. First, the scope of the review was restricted to publications from the WoS and Scopus databases published in English. The study also used the available keywords, as stated in the research method section, to get the available articles. However, some relevant articles may have been missed or considered, hence being the limitation of this study. Thus, one could argue for a more thorough review by extending the selection of publications from other databases, including PubMed, JSTOR, ScienceDirect, IEEE Xplore, Academic Search Complete, etc. However, the pattern of the findings on digital technologies for QA in construction should remain the same. Another limitation lies in the dearth of empirical data on the application of individual digital technology for QA in construction. This is an inevitable aspect of a review, but it may be addressed in the future to confirm the explored directions. Moreover, the study predominantly adopts a qualitative approach. Hence, future research directions could consider the development of quantitative models to measure the impact of digital technology adoption on QA efficiency, cost, and time savings in construction projects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14030844/s1, Table S1: The 56 Selected Relevant Articles. Table S2: Detailed Analysis of the 56 Selected Relevant Articles.

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