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REVIEW PAPERS

# Implementation of industry 4.0 in construction industry: a review

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**Abstract** The article aims to study the literature on Industry-4.0 technologies and "Triple Bottom Line" (social, economical and environmental) parameters in the construction industry. The study focuses on analyzing the gaps in various researches conducted till now and suggests possible information that can be used to improve business processes. Preferred Reporting Items for Systematic Reviews and Meta-Analysis Method is adopted to select the articles. One hundred fifty-six published articles from 2015 to 2023 are examined to understand various theoretical frameworks. Content-based analysis is used for the categorization of five significant categories: (1) Industry 4.0 Enablers; (2) Barriers in Industry 4.0 Adoption; (3) Challenges in Construction Industry; (4) Opportunities for the principle Industry 4.0 Technology; (5) Impact of "Industry 4.0" Technologies. Based on categorization, rewards or incentives, management involvement, employers training, Building Information Modeling, Big Data, Cloud computing, etc., are major enablers of Industry 4.0 in the construction industry. Implementation cost, lack of knowledge, and poor long-term planning are analyzed as common barriers. Numerous challenges and opportunities related to Industry 4.0 technologies have been identified.

Moreover, the Triple Bottom Line impacts of Industry 4.0 technologies, such as waste management, cost reduction, health and security, and resource planning, are also analyzed. The study also revealed that there are numerous research gaps in the integrated application of technology and sustainability because of information inadequacy and unawareness of the stakeholders. The study's findings will help uncover detailed information in a systematical manner for developing an integrated sustainable business environment in the construction industry. The study considering the specific period and inclusion/exclusion criteria can possibly develop limitations of missing a few relevant articles and information in this context.

**Keywords** Industry 4.0 · Triple bottom line · Construction 4.0 · Sustainability · Construction management

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## 1 Introduction

Notable transformations that occurred in different industries and lifestyles prove that the world is accepting Industry 4.0 faster. Irani (2002) mentioned that investment in information systems is a crucial decision, and a compelling investment through logical evaluation provides cutthroat advantages. The fourth revolution has provided better and latest ways of handling the challenges of business. Changes incorporated in the product life cycle, performance rate, production process, and risk management are numerous benefits provided by techniques of "Industry 4.0". Khoumbati et al. (2006) examined the possibilities of "Industry 4.0" in logistics in the context of economy, human resources, and business operations.

Modern technologies such as "Big Data, Artificial Intelligence, 3D printing, Internet of Things, Augmented reality, sensors, and intelligent objects" have provided the most efficient business solutions to complex problems and challenges in different industries (Rahimian et al. 2021; Chauhan et al.

2021; Kumar et al. 2022; Rajput and Singh 2019). Therefore, developing nations focus on learning through innovative technologies instead of borrowing from developed nations, i.e., using 'borrowed' technology (Matos Camarinha et al. 2022).

Technologies of Industry 4.0 have created values by providing additional benefits like low manpower cost, modernized business operations, low inventory instability, and high transparency in logistic operations. Flexibility, quality standards, efficiency, and other benefits can all be seen as outcomes of Industry 4.0. As a result, businesses can fulfill client requests while also creating value. Targets of maximizing profit have attracted industries to implement technologies of Industry 4.0. Therefore, industries have started transforming their processes using the "Industry 4.0" techniques to develop high power, problem-solving and rationalized organization operations. However, the greed for optimizing cost has resulted in ignoring the impacts on the triple bottom line, an aspect of sustainability.

Triple Bottom Line was stamped by Elkington (1994) to present his idea of sustainability in an advanced way. He wrote: "Sustainable development involves the simultaneous pursuit of economic prosperity, environmental quality, and social equity". Elkington elaborated his statement by saying that corporations must prioritize sustainable development and include methods to promote social development and environmental standards along with financial enrichment. Davenport (1994) concluded that infrastructures should be designed to support broad business operations and technical advancements considering organizational goals. Therefore, advancements in technologies, with the rise of the 4th Industrial Revolution, have provided extremely logical models for developing solutions for operations and supply chains (MacDougall 2014). The construction industry, in the integration of the latest technologies of the fourth industrial revolution with intelligent business models, is coined "Construction-4.0". Therefore, construction 4.0 acts as a skeleton to digitally design complex models, developing the latest models for recycling, reconstructing, and creating contemporary attractions.

The article offers a platform to systematically understand various elements linked with sustainable application of "Industry 4.0" in construction. It would help researchers to suggest compatible models and stakeholders to develop effective strategies in improvising business processes.

## 2 Literature review

A literature review is a valid approach for reviewing thoroughly and structuring a research area. A literature study directs the development of the theory and aids in determining the conceptual substance of the research field (Meredith 1993). Researchers and stakeholders are focusing on modern methods to meet sustainability targets. Maqbool et al. (2023) investigated modern methods of construction for the United Kingdom's construction industry and revealed that the technologies of Industry 4.0 support the most for greenhouse emissions and achieving international trade targets. Robayo-Salazar et al. (2023) also showcased the benefits and possibilities of 3D printing in the construction industry. However, the study is limited only to the United States, Europe, and Asia. El Hajj et al. (2023) highlighted that "technological and financial factors are the main barriers to implementing BIM in the UAE". According to Kurniawan et al. (2023), the rise of digital technologies has helped in empowering and transforming construction waste, however, lots of possibilities are still unexplored in the Industry. Demirkesen and Tezel (2022) identified "Resistance to change, unclear benefits and gains and cost of implementation" as significant hurdles in the acceptance of Industry 4.0 adoption in the construction industry. Navaratnam et al. (2022) underlined the "economic, technical, practical, cultural and sustainability aspects" of prefabricated methods of construction. Newman et al. (2021) presented a case study of the United Kingdom reviving the potential of upcoming technologies like "Building Information Modeling (BIM)" in the construction industry, and findings mentioned that limited application of these digital technologies is due to ineffective managerial strategies. According to Fathalizadeh et al. (2022), "Lack of understanding of the potential benefits, insufficient cooperation among practitioners, research institutions and environmental organizations and lack of a systematic approach to pursuing sustainability goals" are the most dominating barriers in achieving sustainable goals in the construction industry. Papa (2021) conducted a study on a real-life Municipal Solid Waste Management System (MSWMS) in India using IOT. Application of modern technologies like "data analytics and artificial intelligence, robotics and automation, building information management, sensors, and wearable, digital twin, and industrial connectivity" is showcased by Turner et al. (2020), and outlined a research proposal for effective application of digital techniques in the construction industry. Müller et al. (2018), also proposed a research model for the effective implementation of Industry 4.0 in the construction industry, and "partial least square structural equation modeling" was undertaken to validate the model. Findings revealed that strategic, social, and environmental are primary drivers, whereas Industrial aggression and potentiality can be major challenges for the implementation of Industry 4.0 along with sustainability. Nowotarski and Paslawski (2017) performed an analysis that shows that major examination is still required in different areas of the construction industry. Findings revealed that no such modernized approach is available to effectively adopt Industry 4.0. Oesterreich and Teuteberg (2016) studied political, economic, social, technological, environmental, and legal implications and proposed the "PESTEL framework and a value chain model" in the acceptance of Industry 4.0 in the construction industry. However, contemporary work related to research in the application of Industry 4.0 technologies in the construction industry is shown in Table 1.

## 3 Research methodology

The study is structured using four methodological conduct recommended by Kitchenham (2004), namely "Data collection, descriptive analysis, category selection, and Data evaluation". Research flow model considered for the study illustrated in Fig. 1.

### 3.1 Data collection

Research articles from more than 27 publications (including journals, conference reports, and books) are sorted to understand the perspective of Industry 4.0 and the triple bottom line. Preferred Reporting Items for Systematic Reviews and Meta-Analysis method is adopted for reviewing and systematic analyses of articles. It is classified into four stages wherein first Phase, different databases like "Google Scholar, web of Science, Science Direct, and SCOPUS" are established. In the second Phase, scrutiny of 228 articles is performed based on title and abstract and by applying query and Boolean operators. Keywords like "CONSTRUCTION 4.0" OR "INTELLIGENT CONSTRUCTION," "INDUSTRIES 4.0" OR "TECHNOLOGIES 4.0", "SUSTAINABLE DEVELOPMENT" OR "SUSTAINABILITY" are selected based on visualization of VOS viewer software (Fig. 4). Moreover, in the visualization, nodes with more surrounding keywords and higher frequencies appear in a deeper color, which signifies the integration of advanced digital technologies with long-term sustainability goals within the construction industry.

In the third Phase, after applying inclusion criteria such as journal, document type, and language, a sample of 197 articles is obtained. The 4th Phase involves screening of eligible research articles to obtain final samples. After eliminating 11 duplicates and 30 articles related to other industries like manufacturing, energy and agriculture etc. based on title, abstract and findings, 156 articles were recognized as most relevant in terms of Industry 4.0 technologies considering sustainability parameters. Figure 2 demonstrates the schema of the literature review.

### 3.2 Descriptive analysis

The distribution of research contributions for the last few years over the map of the world is shown in Fig. 3. Most of the dominant research in the area of "Industry 4.0" and "sustainability" in the construction industry can be seen from countries in South east like Hong Kong, Malaysia, and Singapore, while second, most research is available from countries of Western Asia like Saudi Arabia, Iraq, Iran, and Kuwait. North Eastern European Countries and South American countries, however, also have significant contributions, followed by continents of Eastern Europe, North America, Australia, and New Zealand. Distribution patterns also depict that developing countries from the continents of South Asia, North Africa, West Asia, Central America, and Middle Africa are also putting hard efforts into sustainably developing their construction industry using the digital technologies of "Industry 4.0".

Using VOS viewer software, 156 fully reviewed eligible articles are obtained to plot keyword co-occurrence density map. A higher number of keywords around the node signifies their finer frequency, represented by the intense yellow color shown in Fig. 4. The most prominent and reoccurring keywords used by researchers are "Industry 4.0, sustainability, sustainable development, construction 4.0". Examination and analysis reveal that researchers and stakeholders are aiming to prioritize sustainability goals in the construction industry along with the implementation of Industry 4.0 technologies.

### 3.3 Category selection

Content-based analysis helps in the systematically examination of qualitative data, which allows to formulate concepts per the researcher's needs and interests (Haggarty 1996). Therefore, content based examination of the article emphasizes on detail analyses of categories like "enablers, barriers, challenges, opportunities and impact on triple bottom line" and outline the characteristics of same. The article targets on examination of different digital technologies of Industry 4.0 in construction industry and analyzed the various gaps based on above categories.

### 3.4 Material evaluation

Three researchers carried out validation tests simultaneously using logical and instinctive approaches. Three researchers review data banks and literature reviews to ensure the reliability and originality of the study. To analyze the reliability of the study, Krippendorff (2018) considered the inter-coder-reliability test as "the most general agreement measure with appropriate reliability interpretations" to analyze the reliability of the study. Neuendorf (2017) examined the findings of various researchers and concluded that alpha values of 0.80 or above are acceptable. Hence, the author and two independent observers forwarded the study using SPSS 22.0 along with the aid of Hayes and Krippendorff routines

**Table 1** Contemporary work of Industry 4.0 technologies in construction industry

| Authors | Country | Method/Model/Tool | Analysis type | Contribution |
|---|---|---|---|---|
| Athari Nikooravan and Golabchi (2023) | Iran | Case study Method | Qualitative data | Examine and analyze various barriers of Building Information Modeling (BIM) in Architectural, Engineering and construction industry |
| Hall et al. (2022) | New Zealand | Literature Review and Analytical Hierarchy Process (AHP) | Both quantitative and qualitative | Identified barriers in adoption of Industry 4.0 technology i.e. BIM within SMEs |
| Hwang et al. (2022) | Singapore | comprehensive literature review and pilot interviews | Qualitative data | Examined challenges, propose efficient strategies, investigate perceptions of organizations |
| Bajpai and Misra (2022) | India | Fuzzy-DEMATEL and interpretive structural modeling (ISM) | Both quantitative and qualitative | Examined 14 critical barriers and identified most influencing critical barrier |
| Ogunsanya et al. (2022) | Nigeria | exploratory factor analysis | Qualitative data | Examined the barriers of public aided construction in context of sustainable procurement |
| Al-Yami and Sanni-Anibire (2021) | Saudi Arabia | Case study Method | Qualitative data | Concluded most important benefits and dominating barriers in implementation of BIM in construction Industry |
| Zhou et al. (2021) | Hong Kong | IOT enabled BIM Platform | Qualitative data | Proposed a IOT enabled smart BIM platform to take effective decision for providing on site assembly services on time |
| Gamil et al. (2020) | Malaysia | SPSS Software 22.0 | Quantitative | Identified that absence of "safety and security, documented standards, benefit awareness, improper introduction of IOT and robustness in connectivity" are major challenges in acceptance of IOT in construction Industry |
| Chan et al. (2019) | Hong Kong | structured empirical survey | Quantitative | Examined the distinguish benefits and challenges in implementation of BIM in construction industry |
| Mathiyazhagan et al. (2019) | India | sustainable material assessment model & Fuzzy TOPSIS | Both quantitative and qualitative | Examined the material selection variables, analyzed them and propose model for selecting most appropriate material in terms of sustainability |

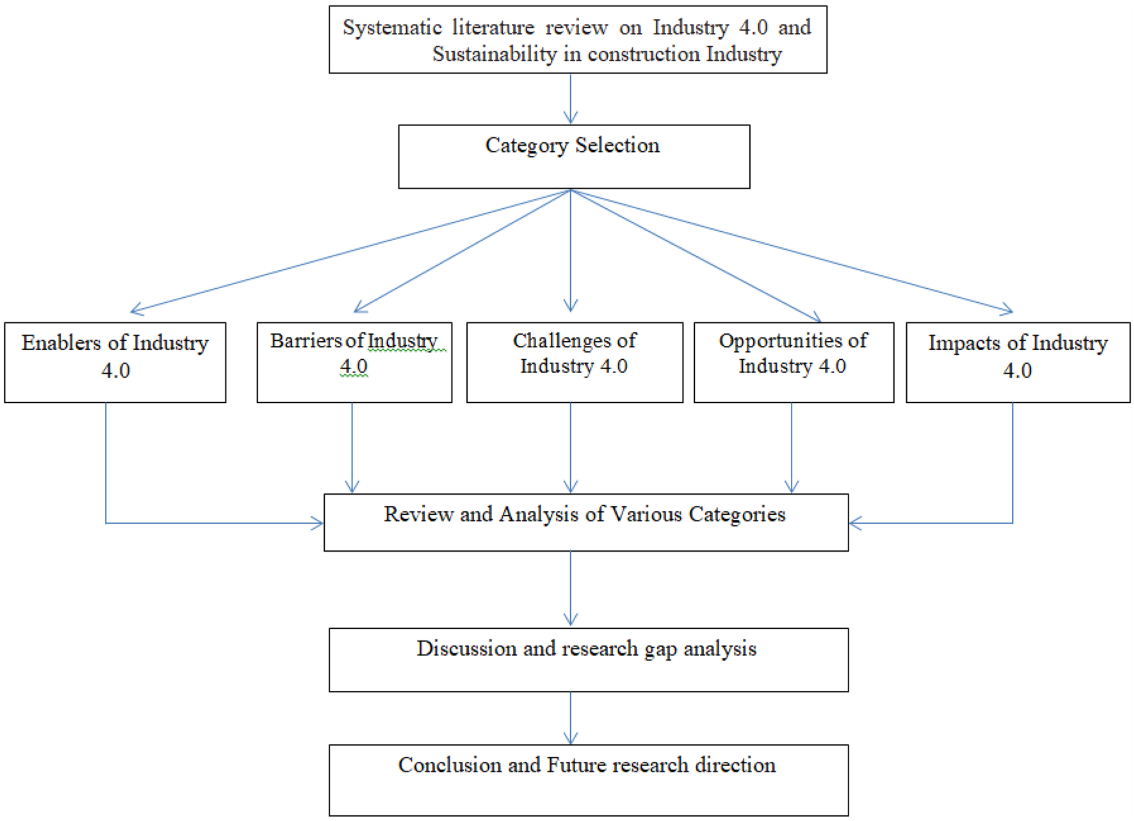


**Fig. 1** Research methodology framework

(2007). Reliabilities inter-coder values were obtained as $\alpha_{rc} = 0.95$ and $\alpha_{rg} = 0.90$, which significantly exceed 0.8. Therefore, the consistency and dependability of the study are reflected.

## 4 Detailed analyses of the literature

In this section literature review of selected articles are considered by analysis and their comprehensive view is presented to establish the current research gaps and future opportunities of research.

### 4.1 Industry 4.0 enablers

The construction industry plays a crucial role in blooming economy of the nation, especially in developing nations like India. Technologies of Industry 4.0 contribute in controlling environmental problems, increasing the performance of operations, and ethically improving in a sustainable manner. Therefore, based on an analysis of different research articles, Table 3 enlists the most efficacious enablers of Industry 4.0 that contribute to integrating construction with technologies of Industry 4.0 considering ethical, sustainable development.

### 4.2 Barriers in industry 4.0 adoption

The 4th Industrial Revolution majorly focuses on technologies that aid in making business operations more efficient and simultaneously achieving sustainability. Industries are making hard efforts to revolutionize their business processes in terms of digitalization and sustainability; however, they are not able to take advantage of globalization at the national and international levels due to the absence of elementary standards of Industry 4.0 and sustainability or the triple-bottom-line. Table 4 represents the view of previous studies that focused on a detailed study of barriers to accepting "Industry 4.0" along with sustainable operations.

### 4.3 Challenges and opportunities

The construction industry still exists as an industry with limited and minimum technological innovations due to

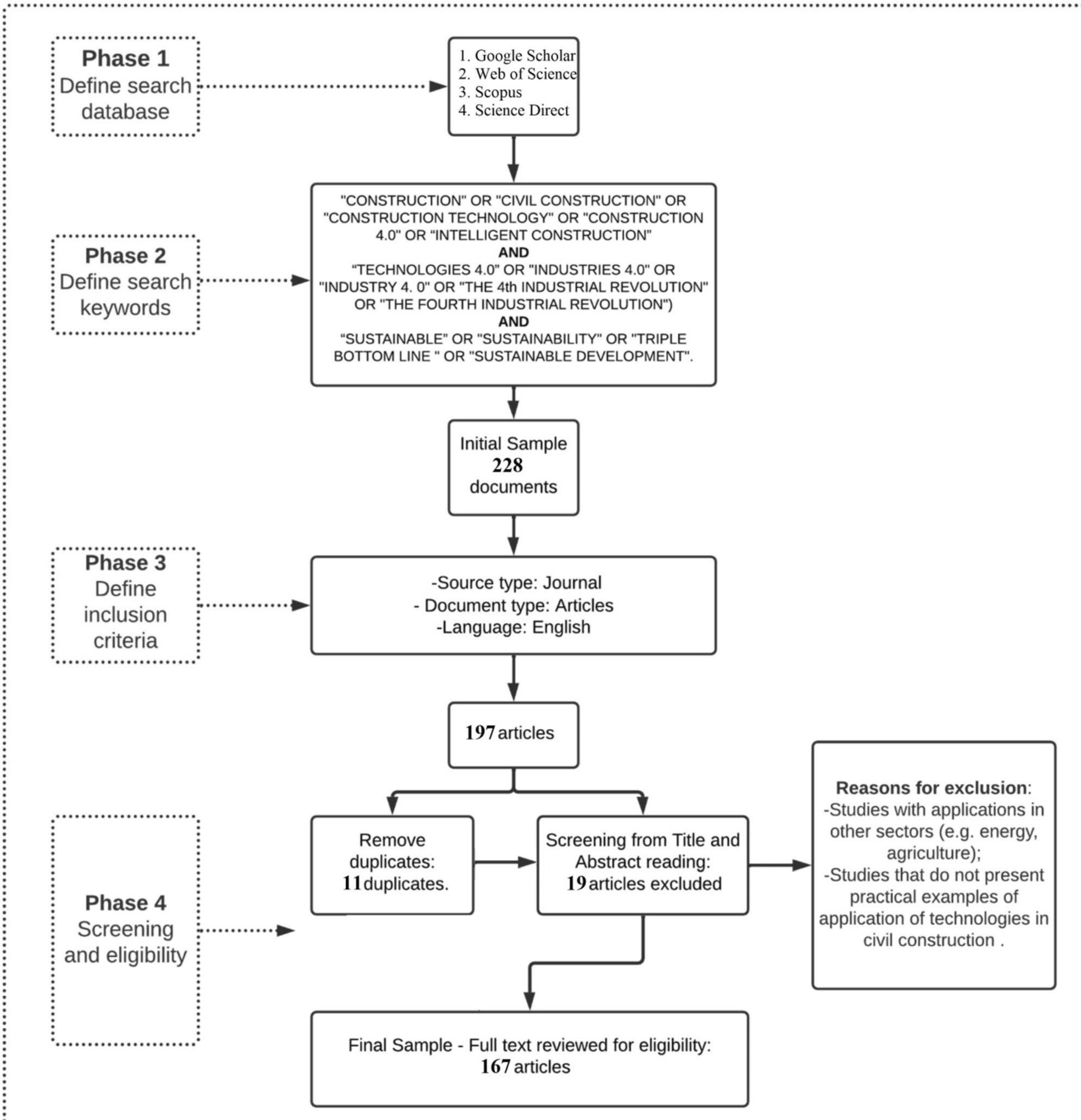


**Fig. 2** Schema of literature review

numerous challenges. Therefore, it is very much essential to understand those demanding situations that resist the development of the construction industry in terms of technological advancements and sustainability parameters impacting the triple bottom line. The acceptance of Industry 4.0 technical innovations overcoming these challenges can generate wide opportunities to meet sustainability standards. Table 5 presents analyses of various challenges of different techniques of Industry 4.0 hired in the construction industry and also a view of wide opportunities associated with different technologies of "Industry 4.0" in the construction industry.

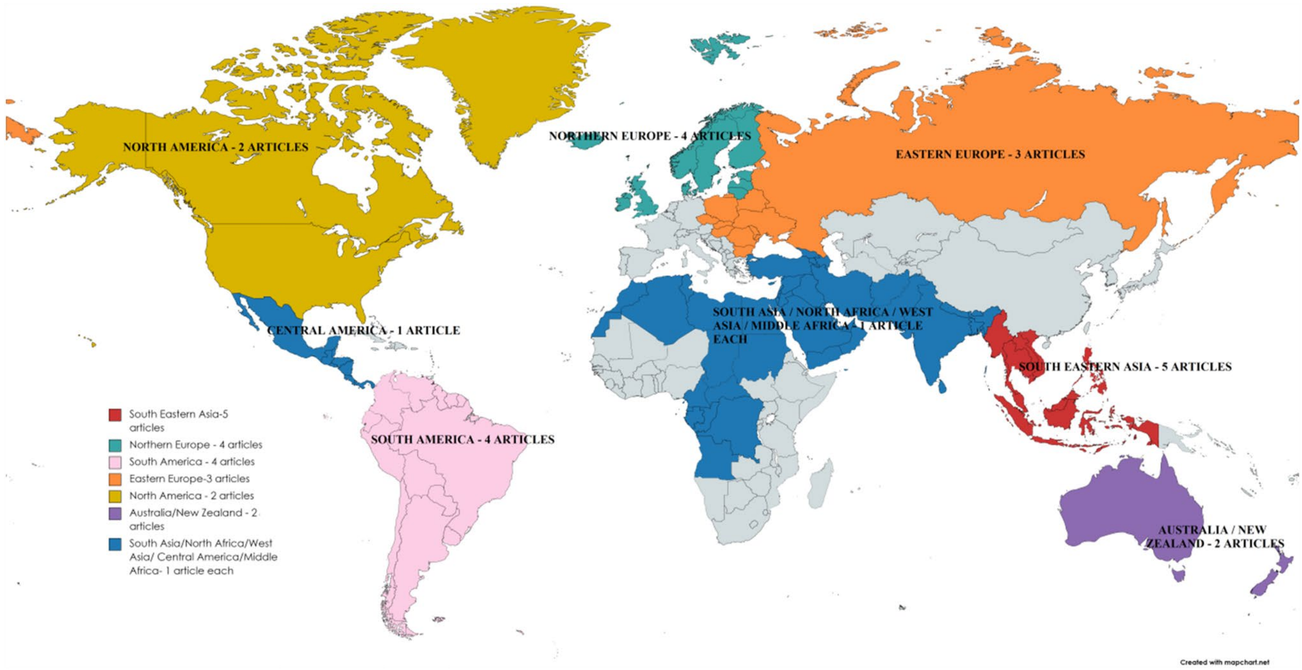


**Fig. 3** Research contribution of different nations in last few years

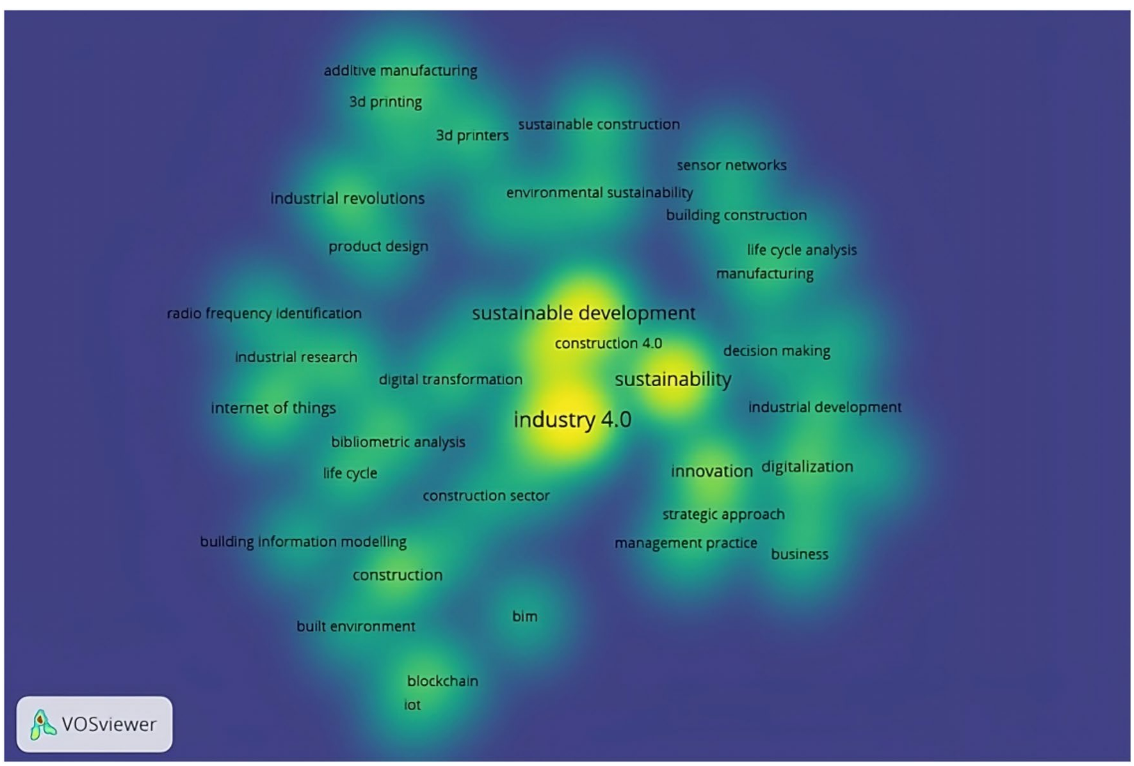


**Fig. 4** Co-occurrence density map of keywords

**Table 2** Most efficacious industry 4.0 enablers

| S.No | Enablers | Description | Reference |
|---|---|---|---|
| 1 | BIM instruments | Effective use of BIM modeling tools in integration with IOT devices in effective management of resources | Tayal et al. 2024; Jemal et al. 2023; Ariono et al. 2022; Abbasnejad et al. 2021 |
| 2 | Digital Twins | Most widely used in regular check and timely maintenance of existing structure | Menegon and Isatto 2023; Hu et al. 2022; Rasheed et al. 2019 |
| 3 | Organizational enablers | Helps in establishing links and design for efficient organizational operability and developing reliable business models | Karnik et al. 2022; Afzal and Lim 2022; Wang et al. 2020 |
| 4 | Agile Manufacturing | Introducing flexibility and agility in design of product by adopting technologies and devices of Industry 4.0 | Bouchard et al. 2022; Babu Loganathan 2022 |
| 5 | "system integration, project-management and competitive pressure" | These factors promotes accepting cloud technology and "Industry 4.0" in small enterprises | Severo et al. 2020; Sony and Naik 2019 |
| 6 | Visual computing | Using computing technologies efficient handling of supply chains and operations for cleaner production | Zhang et al. 2023; Huang et al. 2022; Devi et al. 2021; |
| 7 | Additive manufacturing | Act as tool to modify conventional approaches of design and provide opportunities for new technological strategies for cleaner and efficient production | Jha 2022; Devi et al. 2021; Dong 2020; Nascimento et al. 2019 |
| 8 | Big data application | Analyzes data to develop reliable and smarter decisions as per real challenges to develop sustainable solutions | Yap et al. 2021; Devi et al. 2021; Rasheed et al. 2020 |
| 9 | Integration of Industrial systems | Industrial performance becomes more efficient due to interchange of resources between different Industries | Devi et al. 2021; Nascimento et al. 2019; Rajput & Singh 2019 |
| 10 | Rewards and incentives | Motivates employers to adopt Industry 4.0 sustainable strategies and understand responsibility for society | Latan et al. 2021; Latan et al. 2019; Mani et al. 2018 |
| 11 | Involvement of the management level | Moral behavior and strong commitments from management plays a crucial role in regulating smoother supply chains | Kumar et al. 2020; Schwab et al. 2019; Seuring et al. 2019 |
| 12 | Cloud computing | Promotes greater accessibility to data through extensive sharing strengthens business principles | Devi et al. 2021;Bruin and Floridi 2017 |
| 13 | Applying Block chain | Provides smooth financial operations and helps in regulating flexible economy | Qin et al. 2023; Anjomshoaa and Curry 2022; Valle & Oliver 2020; Rajput & Singh 2019 |
| 14 | Employers training in Industry 4.0 technology with corporate ethics | Based on ethical fundamentals of corporate training for Industry 4.0 to employers aids in develop social responsibility for supply chain management | Seuring et al. 2019; Moktadir et al. 2018 |
| 15 | Using the Internet of Things | IOT aids business to develop logical solutions for production improvement based on sustainability for cleaner production practices | Beekaroo et al. 2019; Liu et al. 2017 |
| 16 | Comprehensive decision making | Systematic and comprehensive decisions aids in achieving in sustainable effectiveness in operations considering ethical standards | Latan et al. 2019; Stoycheva et al. 2018; Latif et al. 2017 |
| 17 | utilizing intelligent Industry tools | Intelligent Industry tools promotes sustainable development based on fundamentals of Triple Bottom Line | Beekaroo et al. 2019;Liu et al. 2017 |
| 18 | Budget promoting Industry 4.0 | Creating necessary funds to support technologies and smart business operations of Industry 4.0 | Yadav et al. 2020; Stoycheva et al. 2018; Latif et al. 2017 |
| 19 | smart supply chain | Technologies of Industry 4.0 helps in developing smart supply chains and creating efficiency in business operations | Gharaibeh et al. 2022; Dallasega et al. 2018; Lu 2017 |

**Table 2** (continued)

| S.No | Enablers | Description | Reference |
|---|---|---|---|
| 20 | Secure industrial practices | Industry 4.0 also ensures employer's privacy and ethical conduct while promoting sustainable development | Leesakul et al. 2022; Mirghafoori et al. 2018; Xu et al. 2016 |

### 4.4 Impacts of "industry 4.0" technologies

Therefore, discussions have summarized Enablers, Barriers, Challenges, and Opportunities in the Context of Industry 4.0 Technologies. However, the study of the impact of these technologies on social, economic, and environmental pillars becomes critical for further expansion and development of Industry 4.0 in the context of Triple Bottom Line. Table 4 illustrates social, economic and environment impacts of Industry 4.0 technologies for further intense research.

## 5 Findings and research gap analysis

The study is based on an examination of previous research articles and a systematic literature review for the effective implementation of Industry 4.0 technologies in the construction industry in the integration of sustainability. Therefore, 156 research articles from 2015 to 2023 are investigated following the approach of Tranfield et al. (2003) and Kitchenham (2004) to offer knowledge and research opportunities for future scope. With regard to the literature review conducted on analyzing the potentials of Industry 4.0 in the construction industry meeting the objectives of triple bottom line an aspect of sustainability, the following findings and research gaps are identified:-

- Table 2 illustrates two types of enablers i.e. technological enablers like Big data, block chain, additive manufacturing etc. whereas managerial enablers like rewards and incentives, corporate trainings, security and privacy etc. are most significant in major literature studies. But efforts to create sustainable and smart built environment by ranking these variables is still scrimpy.
- As illustrated in Table 3, unemployment, Implementation cost, Insufficient support, lack of knowledge, absence of standards and norms, etc., are primary barriers. Factors like stakeholders' resistance and customer feedback are not discussed significantly.
- Table 4 summarizes challenges like security, safety, environmental issues, etc., and opportunities like job opportunities, ease of work, improved living standards, etc., but literature studies lack in providing a relationship of opportunities with challenges for creating a smart, sustainable construction environment.
- Table 5 outlines the social, economic, and environmental impacts of Industry 4.0 technologies to understand and develop a smart and sustainable construction environment, but no model/framework is available to analyze the degree of impact of Industry 4.0 technologies on the triple bottom line.
- No stable framework has been proposed that can motivate companies to integrate their business processes with Industry 4.0 technologies for smart and cleaner construction.

Based on above findings and research gaps the study exposes future directions for effective research towards integrated innovative business processes.

## 6 Implications and future scope

Information technology plays a significant role in reengineering business operations (Gunasekaran and Nath 1997). The study focuses on integrating and abridging the gaps through unmarked opportunities of Industry 4.0 technologies in the construction industry, especially considering their impact on the triple bottom line. Therefore, findings contemplated in scholarly articles point fresh directions for an investigation into the potential research gaps considering sustainable technologies in the primary role. Based on the analysis of research gaps quoted above major implications are clear as follows:

- The study offers integrations between Construction and Industry 4.0 Technologies to achieve better operational and environmental organizational results.
- The study helps to integrate Industry 4.0 technologies in creating a smart and sustainable construction environment.
- The study expands the potential to ensure good construction practices for health and productivity, preserving the environment and economic growth.
- The study exposes research gaps from current research needed to accommodate for creating construction industry as smart and sustainable.
- The study offers information to empirically test enablers, barriers, challenges, and opportunities. This can identify significant variables that influence adoption of Industry

**Table 3** Barriers in industry 4.0 technology adoption

| S.No | Industry 4.0 Barriers | Description | References |
|---|---|---|---|
| 1 | Absence of proper Infrastructure, Reluctance to adopt modern tools and equipment, Poor data management and quality issues, variable monetary benefits, skills inefficiency, job failures, poor technological standards | Ensurity of these factors must be prioritize for smooth and efficient acceptance of technologies of Industry 4.0 | Attiany et al. 2023; Maqbool et al. 2022; Demirkesen and Tezel 2022; Ahmed 2018 |
| 2 | Unavailability of data for decision making, danger of getting unemployed, absence of Information Technology training, bad infrastructure of Information Technology, absence of systematic and planned networks | These barriers are ranked by author to analyze their affect in developing risk reducing strategies | Kumar et al. 2022; Ling et al. 2020; Bhatt and Jani 2019 |
| 3 | Intrinsic and extrinsic barriers | Intrinsic barriers play more crucial role than extrinsic barriers in context of technological digitalization to achieve sustainable business operations | Chauhan et al. 2021; Al Amri et al. 2021; Obiso et al. 2019 |
| 4 | Inefficient digital strategy with resource shortages, absence of standards, norms and structure of affiliations, insufficient maturity in digital technologies | Improper use of digital technologies for depleting resources are broad reasons for developed and developing nations. Challenges of poor standards, laws and certification was issue for developing nations while poor level of maturity was issue for developed nations | Tseng et al. 2022; Wang et al. 2022; Raj et al. 2020; Love et al. 2004 |
| 5 | Implementation Cost | Application of Industry 4.0 technologies increases efficiency, however, its appropriate implementation is crucial. Advise and training on implementing these technologies must be conducted in order to ensure efficient performance | Demirkesen and Tezel 2022; Newman et al. 2021; Nnaji and Karakhan 2020; Griffin et al. 2019; Sarhan et al. 2018 |
| 6 | Technology acceptance | Acceptance of new technologies of fourth revolution by workers becomes difficult due to factors like populism, investment risks, organizational and economic risks | Demirkesen and Tezel 2022; Newman et al. 2021; Nnaji and Karakhan 2020; Sony and Naik 2019 |
| 7 | Talent Development | Skill workforce is an important factor to retain technology in longer run, however use of technologies of Industry 4.0 requires appropriate training and development of personnel | Barbero et al. 2023; Demirkesen and Tezel 2022; Whysall et al. 2019 |
| 8 | Lack of knowledge | Operations are definitely affected by use of technologies of fourth revolution but insufficient knowledge, illiteracy and poor skills creates reluctance to adopt these technologies especially in construction industry | Carlander and Thollander 2023; Fitriani and Ajayi 2022; Trotta and Garengo 2018 |
| 9 | Insufficient Support | Technological users of Industry 4.0 requires on time assistance in case of any need related to issues and queries, however, such failures demotivates them from further use | Prabaharan and Shanmugapriya 2022; Newman et al. 2021; Chan et al. 2019; Oesterreich and Teuteberg 2016 |
| 10 | Poor Long-Term Planning | Absence of long term risks and outcomes while adopting Industry 4.0 | Attiany et al. 2023; Demirkesen and Tezel 2022; Goel et al. 2022; Newman et al. 2021 |

**Table 4** Challenges and opportunities of industry 4.0 techniques

| S.No | Technology | Meaning | Challenges | Opportunities | References |
|---|---|---|---|---|---|
| 1 | Supervised machine learning | Advanced version of machine learning where machines are upskilled with suitable set of data to develop and design output solutions | Presence of appropriate datasets, framework and outcome assessment methods to ensure transparency | Capability of dealing complex datasets and non linear equations, Enhances safety and accuracy in decision process using real time analysis | Rawson and Brito 2023; Baduge et al. 2022; Mirzaei et al. 2022; Xu et al. 2021 |
| 2 | Blockchain | Digital register for storing data that can be shared via network | Data shared are on risk of manipulation creating issues of transparency, safety and privacy related to transactions | Most trusted system for data sharing so huge data can be shared and stored for effective operation of further digital technologies based on datasets | Wu et al. 2023; Kang et al. 2023; Teisserenc and sepasgozar 2021 |
| 3 | Sensors | technological based devices established to gather data and initiate remedial application effectively | Analysis and effective implementation of data depends on physical contact of object, however, lack of appropriate data, technical glitches can result in incorrect decision | Capable of monitoring construction activities, real time analysis and mapping, ensuring safety and efficiency | Rosário and Dias 2023; Fugate and Alzraiee 2023; Rao et al. 2022 |
| 4 | Smart Industrial Robot | Intelligent industrial robots, which combine a manipulator, sensors, and controls, are smart industrial robots | Absence of skills, operational accuracy and credibility, danger of accidents that requires human judgment and intervention | Capable of investigating potential markets and methods to absorb market factors and master in decision making and learning in dynamic challenges | Dörfler et al. 2022; Zhu et al. 2023; Turner et al. 2020 |
| 5 | Digital Twin | Duplicate of the real environment or object to analyze real time operation and performance | Inefficient technical resources, security issues, poor standards, High application cost and skills in construction creates hindrance in improving project lifecycle | Capable of performing real time analysis of progress ensuring safety and standards, planning for resources and maintenance | Honghong et al. 2023; Botín-Sanabria et al. 2022; Teisserenc and sepasgozar 2021; Brum et al. 2021; Hou et al. 2020 |
| 6 | Building Information Modeling (BIM) | Automated platform that uses various virtualization and simulation methods to combine information relevant to construction during project's life cycle | Insufficient availability of data, Information misinterpretation, unpredicted complications | Integrate data related to projects like geometry, material specification, structure design, output and cost of production | Honghong et al. 2023; Khoshfetrat et al. 2022; Lee et al. 2021; Hoang et al. 2020 |
| 7 | | teleoperated devices similar to mini aircraft | Risk involved in operations and danger of accidents or damage in space or greater heights, Constraints of technology and airspace norms | Real time monitoring of site work, Inspection, surveying and maintenance with cost effectiveness and safety | Albeaino et al. 2022; Adepoju 2021; Outay et al. 2020; Kas and Johnson 2020 |
| 8 | Exoskeletons | Robotic device which on wearing boosts human power 20 times | Muscle related Injuries on construction sites due to continuous operations of extreme efforts | Aids in uplifting heavy loaded infrastructure on construction sites to eliminate serious accidents and injuries | Nnaji et al. 2023; Mahmud et al. 2022; Okpala et al. 2022 |

**Table 4** (continued)

| S.No | Technology | Meaning | Challenges | Opportunities | References |
|---|---|---|---|---|---|
| 9 | Augmented Reality | Developing virtual surroundings of the real environment | Designing framework of complex structures in virtual form instead of conventional method and equipment through data collection and implementation | Capable of improving performance through effective documentation and monitoring, managing risk through real time information | Kolaei et al. 2022; Oke et al. 2022; Alirezaei et al. 2022 |
| 10 | Big Data | Huge construction data gathering and storing | Disintegration of data from machinery and processing devices resulting in unpredictable and substandard outputs | Significantly ensures safety on construction sites, waste minimization, Improving quality standards, data collection and support for developing future strategies | Jiang et al. 2023; Munawar et al. 2022; Shooshtarian et al. 2022; Lu et al. 2018 |
| 11 | 3D Printing | Designing of products by continuous addition of layers through specialized printers | Limited automated business frameworks and operations | Aids in faster construction, limiting waste, design enhancement, ensuring process reliability and reducing risks through design verification | Robayo-Salazar et al. 2023; Kazemian et al. 2022; Buchanan and Gardner 2019; Ngo et al. 2018; Lu 2017 |
| 12 | Artificial Intelligence (AI) | computers absorbing and recognizing operations for developing solutions in real time | Difficulties in storing, cleaning and handling of data in integrated form to execute remedial steps in real time | Promote Highly efficient planning and designing of project in terms of event occurrence, cost estimation, waste reduction and risk assessment | Saka et al. 2023; Baduge et al. 2022; Regona et al. 2022; Abioye et al. 2021; Winsun 2016 |

**Table 5** Impacts-industry 4.0 technologies

| S.No | Industry 4.0 Technologies | Social | Economic | Environmental | ReferenceS |
|---|---|---|---|---|---|
| 1 | supervised machine learning | Analysis of real time scenario for taking data based decisions for betterment of society and life style of an individual | Effective decision making algorithms to reduce direct or indirect costs, reliable supply chain and resource management through appropriate cost estimation | Reduces waste generation, develop strategies for changing climate, sustainable development and tackle rebound effect of environment | Lakhouit et al. 2023; Shinde et al. 2022; Shoar et al. 2022 |
| 2 | Blockchain | Expanded association and clarity between collaborator, Data reliability, building information sharing, monitor and handling of harmful matter | Limiting down excessive expenses by reducing in competencies and overhead costs, improves circular economy | Application of reusable and recyclable materials through effective analysis promotes management of waste in lifecycle of project, sustainable building design including resource management | Elghaish et al. 2023; Figueiredo et al. 2022; Woo et al. 2023; Teisserenc and sepasgozar 2021 |
| 3 | Sensors | Sensors preventing ergonomic injuries and the discharge of dangerous substances by tracking worker and environmental health factors | Pollutant monitoring systems are gaining popularity since presence of dangerous contaminants on construction sites are rising, therefore, low-cost sensor technology plays a very crucial role | | Xu et al. 2022; Fokaides et al. 2020; Ahmad et al. 2016 |
| 4 | Smart Industrial Robot | Human robot collaboration enhances quality of work, reduces risk to human life involved in construction, reliable decision making | Saves cost associated with labor, reduces resource wastage, efficient operations improves supply chain | Promotes effective implementation of green technologies and reduces carbon emissions | Wang et al. 2022; Dzedzickis et al. 2021 |
| 5 | Digital Twin | Improving quality of life in society by enhancing designs that reduces carbon emissions and greenhouse effect | Elimination of wastage of resources, funds, time and environmental challenges through pre analysis of product design using digital twin technology, Intelligent and smart green structures | | Yang et al. 2022; Sepasgozar 2021; Teisserenc and sepasgozar 2021; Fokaides et al. 2020 |
| 6 | Building Information Modeling (BIM) | Limiting workplace accidents through safety analysis and ensure population stability by suggesting suitable sites of construction | Enhances operations performance and productivity, Reducing wastages, timely delivery of projects, economical housing, cost estimation and schedule management | Evaluate and control energy output, carbon emissions, conserve resources and enhances waste management | Soust-Verdaguer et al. 2023; Filho et al. 2022; Panteli et al. 2020 |
| 7 | Drones/UAVs | Lack of regulatory and managerial measures for safer operation | Economical technical system | Additional use of cameras and sensors to analyze and address numerous environmental issues | Mahroof et al. 2021; Jeelani and Gheisari 2021 |

**Table 5** (continued)

| S.No | Industry 4.0 Technologies | Social | Economic | Environmental | ReferenceS |
|---|---|---|---|---|---|
| 8 | Exoskeletons | Minimizing organizational tragedies and ensuring health and security | Optimizes cost of training and skilled man power | Makes feasible implementation of complex architectural design, enhances risk management, sustainable regeneration and up gradation life cycle of project | Labò et al. 2023; Vita et al. 2022; Brum et al. 2021; Bellini 2020 |
| 9 | Augmented Reality | Training employees and reducing workplace risks | Financial optimization of resources and efficient budgeting using virtual framework of future operations | Curtailing wastage of resources, accidental disasters, sustainable strategies through pre virtual realization of environment | Senanayake et al. 2023; de Almeida Barbosa Franco et al. 2022; Ahmed 2018 |
| 10 | Big Data | Efficient project management, reliable supply chain, smooth financial operations and easily available information to monitor project progress, competitive benefits in business | | Track, Analyze and control effects of ongoing construction and supports in formulating sustainable strategies using data sets | Woo et al. 2023; Yevu et al. 2021; Choi et al. 2021; Sivarajah et al. 2017 |
| 11 | 3D Printing | Economical and affordable housing | Mass customization and quick deployment, reduces construction cost, no wastage, material planning and limited transportation, improved circular economy | Application of reusable, recyclable and green material, waste reduction and efficient resource planning reduces burden on environment | Gopal et al. 2023; Ibrahim et al. 2022; Caldona et al. 2022; Žujović et al. 2022; Aghimien et al. 2021 |
| 12 | Artificial Intelligence (AI) | Switching from manual to digital improves overall efficiency, hiring continuous labor, and social transferring of expertise from other industries and significant trusted experience of customers | Predict and react to probable risks in project lifecycle, design evaluation, cost optimization, risk elimination, maintenance forecasting and enhancing potential sustainable strategies for construction | | Kulejewski and Roslon 2023; Debrah et al. 2022; Nagy et al. 2021; Choi et al. 2021 |

4.0 along with triple bottom line an aspect of sustainability.

- The study helps companies to develop efficient operational and marketing strategies for smart and green designs.
- The study helps in proposing a framework model for performing smart and sustainable construction activities using Industry 4.0 technologies.

The knowledge shared in this article in form of reference tables will offer great opportunities in theoretical and practical application. It also helps in understanding real world challenges and opportunities. This comprehensive study will open routes for developing sustainable innovative strategies for construction businesses.

## 7 Limitations of the study

Research Gaps analysis revealed that technologies of the fourth revolution are in the preliminary stages of development, but the articles investigated in the study are limited to the time period of 2015 to 2023. This time period is considered on the basis of understanding the most recent challenges and Impacts. This signifies that no study before 2015 can correlate in this regard. Moreover, inclusion and exclusion criteria adopted to review articles have further reduced the count. Therefore, the possibility of missing some relevant articles may exist. It becomes an opportunity for researchers to consider an extended time period in the literature for future scope. Moreover, no framework or model has been presented to provide a significant understanding of the real-world situations of Industry 4.0 and the triple bottom line.

However, the aim of this research article is not to answer specific issues. The goal is to present various elements of Industry 4.0 in the context of the triple bottom line for integrating business processes and creating smart and sustainable construction. Despite its limitations, the paper successfully opens future directions of scope for theoretical and practical implications.

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**Human or animals participants** This article does not contain any involvement of Human Participants and/or Animals.

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