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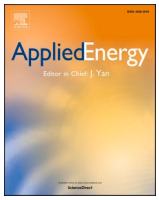

Critical success factors for implementing self-powered wearable internet of things sensors in construction: A systematic literature review and conceptual framework

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HIGHLIGHTS

- A systematic review of SWIoTs in construction was conducted.
- Twenty-eight CSFs were identified and categorized into five domains.
- Two conceptual loop frameworks were proposed and analyzed.
- Key research gaps and future directions were systematically discussed.

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ABSTRACT

With the advancement of wearable electronics, the material properties, energy systems, and applications of self-powered wearable Internet of Things (IoT) sensors (SWIoTs) have been developed and reviewed across various industries. However, no study has identified and categorized the critical success factors (CSFs) for implementing SWIoTs in construction or developed a conceptual framework for their adoption. This study presents a systematic literature review aimed at identifying CSFs, developing conceptual frameworks, and discussing potential applications, research gaps, and future directions. Following PRISMA guidelines, 339 journal articles from the Scopus database were analyzed to extract insights into publication trends, key journals, and research methodologies. The results identified 28 CSFs, categorized into five domains: (1) sensor materials and user comfort, (2) sensor structural design and topology, (3) sensor performance and functionality, (4) system integration and application, and (5) energy harvesting and power consumption. Two loop conceptual frameworks, the classification-based loop conceptual framework and the CSF-based loop conceptual framework, illustrate the interdependence among these CSFs. The potential applications of CSFs for SWIoTs include (1) structural health monitoring, (2) worker safety and human-centric monitoring, and (3) real-time machinery health monitoring. Three key research gaps were identified: (1) optimizing SWIoTs materials for biomechanical resilience and environmental adaptability, (2) advancing mission-critical energy harvesting for building energy systems, and (3) enhancing architecture-agnostic interoperability for large-scale deployment. Future research should focus on ergonomic SWIoTs design, durable and self-healing materials, hybrid energy harvesting, artificial intelligence (AI)-driven energy management, and scalable, interoperable sensor integration. This is the first study to systematically classify the CSFs and uncover the conceptual framework of SWIoTs in the construction industry, thereby contributing to a strategic-level roadmap for their implementation in construction.

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1. Introduction

The construction industry significantly contributes to economic growth through employment, infrastructure development, and boosting gross domestic product (GDP) [1]. As one of the vital sectors, it drives national activities in rapidly growing economies such as China, USA, and UK [2–5]. It accounts for approximately 6 % of the EU GDP and employs around 13.5 million people, underscoring its role in supporting employment and economic growth [6]. Despite its contributions, the construction industry faces health and safety challenges. Nearly three-quarters of all workplace accidents in the EU result in injuries, dislocations, sprains and strains [7]. In the United States, the construction sector accounted for a 5.9 % increase in fatalities resulting from falls, slips, and trips. Notably, over one-third of these injuries were caused by falling to a lower level, with the construction sector accounting for 46.2 % of all such fatal incidents [8]. Given these occupational hazards and safety concerns, adopting advanced technologies to improve workers' safety and project management has become increasingly important in the sector.

In recent years, wearable Internet of Things (IoT) sensing technology has emerged as a promising solution to address health and safety issues in construction. By enabling continuous monitoring of workers' health, safety, and environmental conditions on-site, wearable IoT sensing technology has enhanced resource management and risk mitigation [1,2]. This technology includes devices equipped with sensors that can be worn on the body or attached to items like helmets and safety boots, enabling real-time tracking of physiological metrics (e.g., heart rate) and environmental factors (e.g., temperature, humidity) [3,4]. For example, Spirjakin et al. [5] developed a low-powered, wearable IoT sensor for monitoring gas concentrations and temperature, specifically to improve employees' safety. Their findings demonstrated that the sensor can continuously and remotely monitor combustible gases, thereby enhancing safety in hazardous environments. In a real-world construction setting, such sensors could help prevent incidents by alerting workers to unsafe gas levels in real-time, reducing risks in enclosed spaces like tunnels or basements where ventilation is limited. Similarly, Nath et al. [6] explored the use of wearable smartphone sensors to track construction workers' body postures to identify ergonomic risks associated with musculoskeletal strain. Their results confirmed that these sensors can reliably capture posture data in real-time, offering a practical and cost-effective solution for managing physical strain in labour-intensive settings. For instance, posture-track sensors can alert supervisors when workers repeatedly bend or twist, allowing timely intervention to prevent work-related injuries.

Despite these advancements, wearable IoT sensing technologies might face limitations that could affect their adoption on construction sites. Many wearable sensing technologies rely on intrusive sensors that can cause discomfort for users, potentially impacting wearability and long-term adoption [7]. Additionally, wireless connectivity on construction sites is often unreliable, leading to data transmission issues that hinder real-time monitoring [8]. Moreover, the high power consumption of these devices necessitates frequent recharging, which disrupts continuous monitoring and interferes with construction workflows [9]. To address these limitations, researchers have explored miniaturized energy harvesting devices as alternative power sources to conventional batteries. Autonomous energy conversion from various environmental sources, such as biomechanical movements, water currents, solar radiation, magnetic fields, and wind flow, is becoming increasingly feasible [10–17]. By harnessing these renewable sources, energy harvesters could create fully self-sustaining systems, reducing or even eliminating the need for periodic battery replacement [18].

Building on these advancements, self-powered wearable IoT sensors (SWIoTs) have emerged as a promising solution to address the power limitations of conventional wearable IoT devices [19]. SWIoTs enable continuous and autonomous operation by generating power from the user's environment, making them especially valuable in scenarios where battery replacement or external power access is challenging [20]. For instance, triboelectric nanogenerators (TENGs) are based on triboelectric effect, where friction between two materials generates electrical charges, making them ideal for capturing energy from human motion or environmental vibrations [21]. In construction settings, TENGs can be integrated into workers' safety vests or footwear to capture energy from natural body movements, enabling continuous power generation for monitoring workers' location and activity levels. Piezoelectric nanogenerators (PENGs) convert mechanical stress into electricity through the piezoelectric effect, offering high sensitivity and broad frequency response for applications like structural health monitoring and environmental sensing [22]. For example, in construction environments where heavy machinery generates frequent vibrations, PENGs could utilize this mechanical energy to power sensors that monitor structural deformation and detect potential instability. Other technologies, such as thermoelectric generators (TEGs), photovoltaic cells, and biofuel cells, could contribute to the adoption of SWIoTs by exploiting environmental energy sources like temperature gradients, sunlight, and biochemical reactions, respectively [23].

These advancements collectively enhance the sustainability and autonomy of wearable IoT sensing technologies in diverse conditions. Sunitha et al. [24] developed a self-powered wearable device based on PENGs for real-time health monitoring in remote areas. By converting mechanical energy from walking into electrical power through piezoelectric sensors, their system successfully powers sensors that track vital metrics like SpO_2, body temperature, and pulse rate, transmitting data remotely to facilitate timely medical intervention. In the construction industry, adopting SWIoTs could substantially improve operational efficiency and worker safety. However, successful implementation requires a focus on critical success factors (CSFs), key elements necessary to achieve optimal outcomes. Previous studies in the construction sector have highlighted the importance of identifying critical factors for successful implementation in BIM adoption [25] and PPP waste-to-energy projects [26]. CSFs for SWIoTs implementation in construction can include self-powering capability, real-time monitoring, and reliable wireless communication, thereby contributing to battery replacement frequency, enhanced data reliability, and continuous monitoring capabilities [27,28].

Although previous review studies have examined SWIoTs applications in various scenarios, such as health monitoring and wireless communication systems, they often overlook the construction industry [29]. For instance, Wang et al. [30] explored the design, manufacturing, and application of TENGs in wearable IoT devices, focusing on power efficiency. They found that wearable IoT TENGs have multiple application domains, including energy harvesting for wearable electronics, health monitoring, active sensors, and human-machine interaction (HMI). Similarly, Wang et al. [31] reviewed advancements in PENG-based SWIoT devices designed to monitor human motion and physiological signals, which are particularly valuable for post-pandemic healthcare. Emphasizing piezoelectric materials, their study detailed the mechanisms, material developments, and sensor designs enabling SWIoTs to function autonomously by harvesting energy from human movements. Key applications include continuous monitoring of respiratory rates, heartbeat, joint motion, and environmental interactions, which are crucial for real-time health assessments and predictive healthcare. Lou et al. [32] reviewed the advancements of SWIoT devices, highlighting their role in enabling autonomous, continuous monitoring through energy-harvesting technologies. Key findings highlighted developments in energy-efficient sensors using piezoelectric and triboelectric effects, applied in fields like healthcare and environmental monitoring, thus expanding SWIoTs' potential for real-time data collection without external power sources.

However, these previous review studies rarely addressed the specific needs of the construction industry. Jiang et al. [33] conducted a systematic review and science mapping analysis of SWIoTs in HMI, identifying research gaps and future directions relevant to construction.

Their findings highlighted four primary research themes, including TENGs and PENGs energy harvesting mechanisms, wearable and tactile electronics for sensing, Industry 4.0, and HMI systems, forming a foundation for future applications in the construction industry. Despite these insights, no study has explored the CSFs for implementing SWIoTs, specifically within the construction industry. Given the characteristics of the construction industry, such as high-risk environments and the need for real-time monitoring, a review study of CSFs is critical to enhancing SWIoTs adoption and effectiveness in this field. Addressing this knowledge gap could improve workers' safety and effectively monitor health and environmental conditions in construction settings. Therefore, this study aims to conduct a systematic literature review of CSFs for implementing SWIoTs, identifying a unified set of CSFs, potential applications, research gaps, and future research directions. The specific research objectives include: (1) to analyze the annual publication trends, peer-reviewed journals, geographical context, and research methods of CSFs for SWIoTs implementation in construction; (2) to identify and categorize the CSFs for implementing SWIoTs in the construction industry; (3) to highlight the potential applications and develop conceptual frameworks to enhance the implementation of SWIoTs in construction; and (4) to discuss the research gaps and future research directions on the CSFs for implementing SWIoTs in construction.

The remainder of this paper is as follows. Section 2 discusses existing literature on the applications and challenges of wearable IoT technologies in construction, as well as research gaps and CSFs of SWIoTs in construction. Section 3 outlines the methodological framework used to identify relevant articles on the studied topic. Next, Section 4 provides the results, highlighting the annual publication trends, peer-reviewed journals, geographical context, research methods, and CSFs for implementing SWIoTs in construction. The potential applications, conceptual frameworks, research gaps, and future directions are discussed in Section 5. Lastly, Section 6 summarizes the conclusions, contributions, and limitations.

2. Related works

2.1. Applications and challenges of wearable sensing IoT technologies in construction

In the construction industry, wearable sensing technologies are used to enhance safety and health monitoring by providing real-time data on workers' biomechanical, physiological, and on-site environmental measurements [6,34,35]. For example, IoT-enabled helmets, vests, and wristbands can continuously monitor bodily movements and health signals such as acceleration, heart rate, temperature, and detect hazardous gases like carbon monoxide [5,36,37]. For instance, photoplethysmography (PPG) sensors embedded in wristbands can measure cardiovascular strain by calculating heart rate variability [38,39], while electrocardiography (ECG) sensors offer precise monitoring of heart rate, helping detect arrhythmias or other stress-related cardiovascular conditions [40]. Additionally, surface electromyography (sEMG) sensors can measure muscle strength and detect muscle fatigue, thereby aiding in identifying work-related risk factors during heavy equipment operations and manual handling tasks [41].

Beyond physiological measurements, advanced neuroimaging sensing technologies such as electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) are utilized to assess cognitive load and mental stress or fatigue [42,43]. EEG sensors can monitor brain activity associated with attention and relaxation, although they are prone to signal artifacts [44]. By contrast, fNIRS can measure brain oxygenation, offering greater stability in dynamic construction environments and has superior spatial resolution [45]. Furthermore, inertial measurement units (IMUs) with accelerometers and gyroscopes can measure human movement patterns, enabling the assessment of physical fatigue, fall prevention, and awkward working postures [46].

Other wearable IoT sensors can enhance predictive maintenance and safety hazard prevention. For example, insole pressure systems can measure gait stability and awkward working postures to identify fall risks in high-risk areas [47]. Electrodermal activity (EDA) sensors, which measure skin conductance, can monitor stress levels in high-pressure environments where stress can impair focus [48]. Body-worn cameras and smartphones equipped with motion sensors can further enhance health and safety monitoring by capturing workers' activities, biomechanical parameters, and safety hazards [49].

However, deploying wearable IoT technologies in construction presents several challenges. First, data privacy is a critical concern due to the sensitivity of health records and behavioral data collected from workers [50]. Robust data protection measures, such as encryption, anonymization, and strict access controls, are essential for safeguarding workers' information [51]. Second, effective data management practices, including secure data storage and regulated data access, are necessary to comply with privacy regulations and uphold workers' trust [52]. Third, power consumption and device durability in extreme on-site environments are other challenges that often impede continuous monitoring, especially on remote sites with limited charging options [53]. To address these issues, researchers have explored TENGs and PENGs for energy harvesting. TENGs can convert low-frequency mechanical energy into electric signals from body movements, offering advantages such as broad material selection, simple structure, and low cost, making them well-suited for wearable applications [30]. Similarly, PENGs can harness biomechanical energy, enabling reliable monitoring of motion and physiological signals [31]. Both technologies aim to improve device sustainability and reduce dependence on external power sources, which are particularly advantageous for implementing SWIoTs in construction environments. Table 1 illustrates the applications and challenges of wearable sensing IoT technologies in construction.

2.2. Research gaps and CSFs of SWIoTs in construction

In this study, CSFs are strategic elements or applications requiring continuous monitoring to ensure outcomes essential to project-specific and organizational goals [77,78]. Building on this foundational concept, previous research has examined CSFs for implementing wearable sensing technologies in construction, especially in safety and health monitoring [28,79–85]. Within high-risk construction environments, Awolusi et al. [79] identified key CSFs, including trialability, feature utility, and availability of qualified personnel, with trialability ranked as the most critical factor (mean score 6.15 out of 7). Yin et al. [85] supplemented these findings by highlighting barriers to adoption, such as comfort issues, data privacy concerns, and indirect costs, emphasizing the importance of aligning wearable sensing technologies' features with usability and workforce readiness. These studies collectively underscore the necessity for tailored wearable sensing technology solutions in developed economies.

In contrast, research in developing countries has highlighted distinct priorities driven by infrastructural and economic constraints. Fernandez et al. [82] emphasized the significance of leadership, technology awareness, and interoperability for IoT device adoption in the Dominican Republic, particularly in decentralized environments. Similarly, Tetteh et al. [83] employed a fuzzy synthetic evaluation model within the technology–organization–environment (TOE) framework to examine wearable sensing technologies adoption in the Ghanaian construction industry. Their findings revealed that perceived value, technical know-how, security, top management support, competitive pressure, and trading partner readiness are critical drivers for adoption. These findings demonstrate the critical role of firm-level characteristics, such as competitive pressure and organizational leadership, in driving wearable sensing technologies adoption.

Ibrahim et al. [81] expanded this discourse by examining the benefits and barriers of wearable sensing technologies in Nigeria. Their study identified significant advantages, including collision avoidance, electrocution prevention, and reductions in slips and falls. However, high

Table 1
Applications and challenges of wearable sensing IoT technologies in construction.

Sensor type	Applications	Challenges	Sources
Internet of Things (IoT)-based devices	Continuous monitoring of bodily, physiological, and environmental signals	Durability in harsh environments, Power shortage, data security, and privacy	[5,36,37,54]
Photoplethysmography (PPG) sensors	Assessing cardiovascular strain by calculating heart rate variability	Environmental light interference, power shortage	[38,39,55,56]
Electrocardiogram (ECG) sensors	Detecting arrhythmias or stress-related cardiovascular conditions	Signal artifacts affecting accuracy, data security, and privacy	[40,56]
Surface electromyography (sEMG) sensors	Preventing injuries during manual handling tasks and heavy equipment operations by detecting muscle fatigue	Requirement for precise sensor placement, body discomfort or intrusiveness, battery life maintenance	[41,57–60]
Electroencephalography (EEG) sensors	Monitoring brain activity is associated with attention and relaxation.	Susceptibility to motion artifacts, data security, and privacy	[34,44,61–63]
functional Near-Infrared Spectroscopy (fNIRS)	Measuring brain oxygenation levels for stability in dynamic environments	High cost, power shortage	[45,64–66]
Inertial Measurement Units (IMUs)	Assessing physical strain, preventing falls, and monitoring awkward working postures	Accuracy in capturing motion patterns in dynamic settings, and battery life maintenance	[46,67–69]
Insole pressure systems	Evaluating gait stability and posture to identify fall risks in high-risk areas.	Affected by construction site conditions, battery life maintenance.	[47,70–72]
Electrodermal Activity (EDA) sensors	Monitoring stress levels in high-pressure environments	Affected by sweat and skin humidity, data security and privacy	[48,73]
Smartphones with motion sensors	Monitoring worker activities with a versatile, accessible real-time tracking method	Limited battery life, data security, and privacy.	[49,74–76]

procurement and maintenance costs, insufficient training, and inadequate information technology infrastructure were notable challenges. These findings align with global trends but underscore the urgency of affordable and scalable solutions in resource-constrained contexts [28]. From a broader perspective, prior research has consistently emphasized the importance of technological compatibility, user adaptability, and seamless data integration for the successful implementation of wearable sensing technologies in the architecture, engineering, and construction (AEC) sector [28]. Complementing these insights, Okpala et al. [86] proposed a success model to assess the adoption and impact of wearable sensing devices in construction. Their study integrated adoption-related variables with implementation success indicators to evaluate effects on worker performance and project outcomes. Their results demonstrate how critical factors can be systematically linked to measurable impacts, reinforcing the need to identify and validate CSFs tailored to SWIoTs implementation in construction. Collectively, these insights highlight that while developed economies prioritize interoperability and workforce readiness, developing countries should overcome affordability and infrastructure limitations to facilitate adoption.

Despite substantial progress, the CSFs for implementing SWIoTs in construction have not been explored and remain a critical research gap. A deeper understanding of CSFs for implementing SWIoTs is essential to address the practical needs of the construction industry. To bridge this gap, this paper develops two conceptual loop frameworks focused on construction-specific requirements. By enhancing worker safety, health monitoring, and operational efficiency, this framework aims to advance SWIoTs integration and provide actionable strategies for both developed and developing regions. Ultimately, this paper aims to conduct a systematic literature review of CSFs for implementing SWIoTs, identifying a unified set of CSFs, potential applications, research gaps, and future research directions.

3. Research methods

This paper adopted a systematic literature review to synthesize and evaluate published articles related to the studied domain. The primary goal of the systematic literature review is to analytically identify and summarize relevant published studies to achieve the research objectives while minimizing potential bias and random error [87,88]. To ensure transparency and rigor in the reporting process, this paper adhered to the 2020 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [89–91], as illustrated in Fig. 1. The figure outlines the four main steps (i.e., identification, screening,

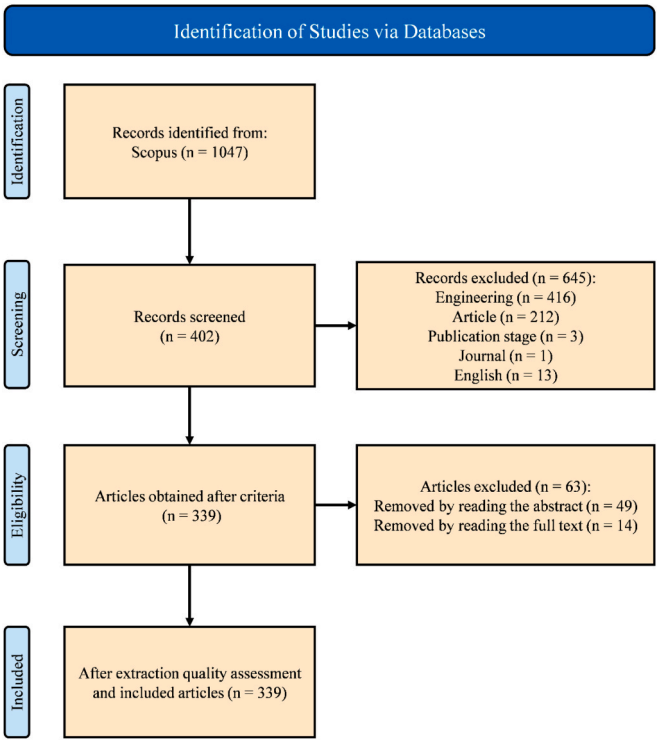

Fig. 1. A PRISMA flow diagram indicating relevant articles of CSFs for implementing SWIoTs in construction.

eligibility, and inclusion of articles) and shows the number of retrieved articles during each step. The PRISMA 2020 framework also provides a comprehensive 27-item checklist that offers a standardized methodology for consistent and thorough documentation and reporting of findings [92]. It could help to address key concerns related to bias, reproducibility, and overall quality in the review process. By adopting the PRISMA guidelines, this paper addresses bias, data reliability, and validity of findings, enhancing the credibility and reproducibility of the review [93].

3.1. Identification

The step aims to establish a comprehensive dataset for analyzing the CSFs of SWIoTs, particularly applicable in engineering-related domains. The Scopus database was selected as the primary electronic database due to its extensive coverage of peer-reviewed academic journals, conference proceedings, and multidisciplinary research outputs [94–96]. Moreover, Scopus was chosen over other databases, such as Web of Science and IEEE Explore, because of its broader scope and its ability to capture a wide range of studies relevant to both technological advancements and applied research in engineering-related contexts [97].

To identify relevant articles, a structured search query was designed and implemented using carefully selected keywords. The search utilized keywords such as "self-powered" combined with "wearable OR Internet of Things OR IoT OR sensors" and "critical OR success OR factors OR drivers." These keywords were developed to target extant literature that explored the integration of self-powered wearable devices with IoT technologies and sensor systems while identifying their CSFs. Boolean operators (e.g., AND, OR) were employed to ensure precision and relevance in the search results. The query was applied to the fields of "Article title, Abstract, Keywords" within Scopus, ensuring the retrieval of a targeted yet comprehensive dataset. The search process was conducted without applying restrictions on publication year, journal type, or geographical region, allowing for the inclusion of both foundational studies and recent advancements in the field. This inclusive approach resulted in an initial dataset of 1047 documents. These results provided a solid foundation for subsequent screening and refinement, confirming that the identification process remained systematic, transparent, and replicable for other researchers.

3.2. Screening

This step ensures that only the most relevant and reliable sources are selected for analysis. It was necessary to narrow the scope of the study and focus on high-quality research that aligns with the specific objectives. In this study, specific inclusion criteria were applied to refine the search results. These criteria included subject area (engineering), document type (article), source type (journal), publication stage (final), and language (English). First, the subject area was limited to "Engineering" because this paper focuses on construction, a discipline closely associated with the engineering domain. This restriction affirmed that research from unrelated subject areas was excluded. Second, the screening was confined to journal articles, as they are typically peer-reviewed, comprehensive, and report validated insights compared to other publication types, such as conference papers, which often lack the same level of detail and rigor [98]. Third, the language was restricted to "English", the dominant medium of scientific communication, which confirms accessibility to a broad international audience of researchers [99]. Lastly, only articles in their final publication stage were included to exclude incomplete or preliminary studies, facilitating finalized and robust findings.

Table 2 shows the keywords and search results from the Scopus database. The search was conducted in January 2025, and 402 articles were obtained after the screening process.

Table 2
Keywords and literature search results from the Scopus database.

Item	Search Category	Results	Search string
1	Identification	1047	(TITLE-ABS-KEY (critical OR success OR factors OR drivers) AND TITLE-ABS-KEY (self-powered AND wearable OR internet-of-things OR iot OR sensors))
2	Screening	645	(LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (SRCTYPE, "j"))
3	Combined	402	1 AND 2

3.3. Eligibility

At this stage, the primary objective was to read and identify articles related to CSFs of implementing SWIoTs relevant to engineering-related domains, particularly within the construction industry. To achieve this, a systematic filtration process was conducted to exclude studies outside the scope of this research. This process involved a detailed review of the titles, abstracts, and full texts of the 402 articles. Such a rigorous approach ensured that only the most relevant studies were included, resulting in a refined and high-quality dataset for subsequent analysis.

To ensure clarity and relevance, the eligibility criteria were defined as follows. Articles were included if they (1) explicitly demonstrated the application of SWIoTs in the construction industry, (2) exhibited potential use of SWIoTs in engineering applications, even if explicit statements of construction applications were not provided, and (3) possessed key drivers or success factors of SWIoTs, such as wearability, IoT capabilities, and self-powering features. Conversely, articles lacking relevance to the construction industry or missing CSFs of SWIoTs were excluded. For instance, in the domain of smart agriculture, Peng et al. [100] proposed a hybrid wind energy harvesting device for monitoring agricultural environmental parameters, while Wang et al. [101] developed a vibration-powered sensor for agricultural machinery. Although they demonstrated CSFs of SWIoTs, these studies were excluded as they focused on agricultural applications rather than engineering related domains such as the construction industry. Similarly, Hudson et al. [102] introduced a self-powered sensor for subsea annulus monitoring, while Wang et al. [103] and Chen et al. [104] developed ocean-wave-powered sensors for wave height measurement and marine structural monitoring. While these articles showcased advancements in energy harvesting and monitoring technologies, their focus on marine applications rendered them outside the scope of this research. Eventually, 63 journal articles were removed, while 339 articles were deemed eligible in the next step.

3.4. Included articles, data extraction, and quality assessment

This paper retained 339 journal articles for subsequent analysis. The bibliographic data for these articles was retrieved from the Scopus database and exported as a ".csv" file to facilitate data processing. The extracted data comprised author names, article titles, keywords, abstracts, publication years, journal titles, and among others. Following the guidelines of Kitchenham and Charters [105], a quality assessment was conducted using the checklist outlined in Table 3, which has been employed in similar studies [33,106,107]. Although the restriction to Scopus-indexed journal articles already ensures a baseline of peer review and academic quality, applying this checklist remained necessary. As recommended by PRISMA 2020, quality appraisal is an integral step in systematic reviews to ensure transparency, consistency, and methodological rigor. Beyond confirming peer-review status, the checklist also evaluates aspects such as clarity of research objectives, appropriateness of methods, and validity of findings, thereby ensuring that only

Table 3
Checklist of quality assessment.

No	Checklist
1.	Are the aim and objectives clearly stated?
2.	Is the reporting logical, cohesive, and coherent?
3.	Is the proposed technique well described?
4.	Is the used research methodology appropriate for the objectives?
5.	Are the methods for data collection adequately depicted?
6.	Do the explanations and conclusion hinge on the data?
7.	Is there a tangible and substantial contribution to knowledge?
8.	Are the aims and objectives fulfilled?
9.	Is the research process well documented?
10.	Is the study reproducible?

articles meeting both bibliographic and methodological standards were included. Publications that met at least 70 % of the checklist criteria were deemed eligible for further consideration in this study. Importantly, all the included journal articles successfully passed the quality assessment, confirming their suitability for subsequent analysis and discussion.

4. Results

4.1. Annual publication trend

Fig. 2 illustrates the annual publication trends of research articles on CSFs for implementing SWIoTs in construction from 2010 to January 2025 (2025J). As shown in Fig. 2, an upward trajectory in the number of publications is evident, reflecting the growing interest in this field. Between 2012 and 2016, the development of CSFs for implementing SWIoTs in construction was relatively reserved, with the number of articles gradually rising from 3 in 2012 to 12 in 2016. This limited growth can be attributed to the nascent stage of IoT technologies and the early developmental phase of SWIoTs. With the recent technological advancements in energy harvesting and the increasing demand for wearable sensing technologies, there is a greater clarity in the development path for SWIoTs, which might lead to a rise in the number of publications from 2017 onward. For instance, the number of publications increased from 22 in 2018 to 24 in 2019, and further to 32 in 2020, highlighting an acceleration in scholarly interest during this period.

A significant increase in publications occurred in 2021, with 44 published articles, representing a 37.5 % increase compared to 2020. This surge may likely be driven by the heightened interest in wearable health-monitoring devices during the global pandemic. Another significant leap was observed in 2023, with 65 published articles, a 96.97 % increase compared to 2022. This growth can also be attributed to the integration of sustainable energy solutions and smart health applications, which further accelerated advancements in the field. In 2024, the number of publications increased to 69 articles, indicating an upward trend. Since the search strategy was conducted in January 2025 (2025J), it obtained only 8 articles, reflecting a partial data collection period rather than a decline in research activity. To forecast the number of publications throughout 2025, multiple fitting approaches were employed. In addition to a polynomial fit, we applied a linear fit based on the last two years (2023–2024) and an exponential fit based on the overall trend. These fitting approaches resulted in approximately 73, 69, and 82 publications, respectively, suggesting a possible range from 69 to 82 publications. Taking the mean value as a tentative reference, around 75 publications could be expected in 2025. In summary, research on CSFs for implementing SWIoTs in construction has experienced rapid growth over the past decade, gaining substantial attention from both industry and the academic community. The growth and interest in the studied topic are expected to continue in the coming years, thus driving innovations in health monitoring, environmental sensing, and sustainable energy harvesting technologies.

4.2. Journal sources

Based on the analysis of journal sources, articles on CSFs for implementing SWIoTs in construction are primarily published in numerous journals. Table 4 lists the top 15 journal sources, which together account for a substantial share of published articles in this field. These journals cover various disciplines, including nanotechnology, materials science, energy, and engineering, reflecting the multidisciplinary nature of this research study. Among them, *Nano Energy* is the leading journal with 114 articles, representing 33.63 % of the total publications. It focuses on nanotechnology and energy systems, aligning closely with the core topics of SWIoTs. Next, *Chemical Engineering Journal* was ranked second with 24 articles (7.08 %), followed by *ACS Nano* (14 articles, 4.13 %) and *Advanced Materials Technologies* (13 articles, 3.83 %), with research scope on advanced materials and nanotechnology.

Other notable journal sources include *IEEE Sensors Journal* (11 articles, 3.24 %) and *Applied Energy* (10 articles, 2.95 %), which focus on sensor technology and energy systems, demonstrating critical areas in this research domain. Additional journals, such as *Smart Materials and Structures* (9 articles, 2.65 %), *Sensors* (7 articles, 2.06 %), and *Advanced*

Fig. 2. Annual publication trends of CSFs for implementing SWIoTs in construction. Note: 2025J means that articles published in 2025 only include those retrieved before January.

Table 4
Top 15 selected journal sources.

Journal	Count	Percentage
Nano Energy	114	33.63 %
Chemical Engineering Journal	24	7.08 %
ACS Nano	14	4.13 %
Advanced Materials Technologies	13	3.83 %
IEEE Sensors Journal	11	3.24 %
Applied Energy	10	2.95 %
Smart Materials and Structures	9	2.65 %
Sensors	7	2.06 %
Advanced Materials	6	1.77 %
Energy	6	1.77 %
IEEE Access	5	1.47 %
Nano-Micro Letters	5	1.47 %
Sensors and Actuators A: Physical	5	1.47 %
Journal of Alloys and Compounds	4	1.18 %
Journal of Electronic Materials	4	1.18 %

Materials (6 articles, 1.77 %), further illustrate the broad scope of this field, spanning from smart materials to practical applications. Several highly regarded journals, including *IEEE Access*, *Nano-Micro Letters*, and *Sensors and Actuators A: Physical*, each contributed to 5 articles (1.47 %), while *Journal of Alloys and Compounds* and *Journal of Electronic Materials* each published 4 articles (1.18 %). In addition to the journals presented in Table 4, a total of 102 journal sources collectively contributed 30.1 % of the total publications. These prominent and widely known journals illustrate the extensive scope of this research field, which encompasses several disciplines, including advanced nanotechnology, cutting-edge materials science, innovative energy solutions, practical applications in engineering, and wearable IoT technologies. It also demonstrates the far-reaching impact and relevance of research on CSF for implementing SWIoTs in construction, while simultaneously suggesting opportunities for more thematic consolidation to enhance research visibility and impact.

4.3. Geographical distribution of articles

Table 5 presents a geographical analysis of research articles on CSFs for implementing SWIoTs in the construction industry, focusing on the top 15 contributing countries. In this study, the country of each article was determined by the address of the corresponding author. China leads this field with 195 articles, accounting for 57.52 % of the total publications. This dominant position highlights China's strong interest in advanced materials, energy harvesting, and wearable IoT technologies. The United States ranks second with 45 articles, representing 13.27 % of the total. Despite a lower publication outcome, the United States showed a notable impact with 2204 citations and an average of 48.98 citations per article, slightly exceeding China's average of 48.68 citations per article. South Korea ranked third with 22 articles (6.49 %), contributing to 965 citations and an average of 43.86 citations per article. Other notable countries include Taiwan (12 articles, 3.54 %) and the United Kingdom (16 articles, 4.72 %), showcasing active participation from regions with strong technological and engineering research capabilities. Although Hong Kong obtained only 6 articles (1.77 %), it achieved an exceptionally high average of 66.17 citations per article, demonstrating its ability to produce impactful research despite a smaller volume of publications.

Table 5
Top 15 countries/regions in CSFs for implementing SWIoTs in construction.

Country	Documents	Citations	Average citations	Percentage of total articles
China	195	9493	48.68	57.52 %
United States	45	2204	48.98	13.27 %
South Korea	22	965	43.86	6.49 %
Taiwan	12	437	36.42	3.54 %
United Kingdom	16	424	26.50	4.72 %
Hong Kong	6	397	66.17	1.77 %
Singapore	3	136	45.33	0.88 %
India	9	115	12.78	2.65 %
Italy	2	80	40.00	0.59 %
Germany	5	45	9.00	1.47 %
Japan	3	31	10.33	0.88 %
Egypt	1	27	27.00	0.29 %
Brazil	1	26	26.00	0.29 %
Turkey	1	21	21.00	0.29 %
Iran	3	14	4.67	0.88 %

Countries such as India (9 articles, 2.65 %), Germany (5 articles, 1.47 %), and Italy (2 articles, 0.59 %) also contributed to the field. Notably, Italy achieved an average of 40.00 citations per article, indicating a focus on quality over quantity. Meanwhile, Japan, Singapore, and Egypt each contributed 3 or fewer articles but displayed varying levels of influence. For example, Singapore received an average of 45.33 citations per article from 3 articles, reflecting the high impact of its contributions. In addition to the countries listed in Table 5, other countries collectively contributed to 15 articles, accounting for 4.47 % of the total publications. This geographical analysis highlights that research on CSFs for implementing SWIoTs in construction is concentrated on a few leading countries, particularly China and the United States, which together account for over 70 % of the total publications. At the same time, countries like Hong Kong, Singapore, and Italy demonstrate the potential to achieve significant impact even with smaller publication volumes. Overall, these results underscore the importance of international collaboration in advancing this emerging research field across continents in developed and developing countries.

4.4. Methods of CSFs for implementing SWIoTs in construction

The research methods employed in the 339 retrieved articles from Scopus were analyzed to identify the predominant approaches used in the study of CSFs for implementing SWIoTs in the construction industry. All data collection methods employed in each article were recorded, with some articles utilizing multiple research approaches. Table 6 illustrates the methods of CSFs for implementing SWIoTs in construction. As shown in Table 6, the most frequently adopted methodology is the laboratory experiment, with 332 occurrences, reflecting a strong emphasis on controlled testing environments for validating sensor performance and functionality. Many researchers have focused on the fabrication, testing, and characterization of SWIoTs and sensor materials [108–112]. For instance, Chen et al. [113] and Pang et al. [114] conducted laboratory experiments to evaluate the energy harvesting performance and optimization strategies of wearable thermoelectric generators (W-TEGs). Their experimental setups employed controlled temperature gradients and integrated heat dissipation mechanisms to simulate real-world conditions. Key performance metrics, including output voltage, power density, and thermal resistance, were systematically measured under varying environmental conditions to assess the efficiency and feasibility of the proposed W-TEG configurations. For sensor material characterization, advanced techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDX), Raman spectroscopy, and X-ray photoelectron spectroscopy (XPS) were widely utilized to analyze crystallinity, morphology,

Table 6
Summary of research methods of CSFs for implementing SWIoTs in construction.

Method	Count	Selected References
Laboratory experiment	332	[108,132–135]
Simulation	180	[136–140]
Field experiment	160	[121,141–144]
Theoretical model	50	[113,145–148]
Expert evaluation	1	[131]

elemental composition, chemical states, and structural properties [115,116]. These characterization methods are crucial for verifying material performance and ensuring their suitability for integration into SWIoTs. Such laboratory-based evaluations play a pivotal role in optimizing sensor design, structural integration, and energy efficiency, bridging the gap between prototype development and real-world deployment.

The second most common research approach is simulation, which appeared in 180 articles, underscoring its vital role in modeling, predicting, and validating system behavior before real-world deployment. In many cases, simulations bridge the gap between theoretical concepts and practical applications by enabling researchers to optimize designs, refine performance parameters, and understand the underlying mechanisms driving SWIoTs. A wide range of software tools, including MATLAB [117], COMSOL [118–120], LTspice [121], and VASP [122] have been utilized to simulate electrical output, power management circuits, and material behavior under various conditions. For example, a study employed Finite Element Method (FEM) simulation in COMSOL Multiphysics to investigate the charge transfer and power output characteristics of a multi-output AC/DC TEG, with experimental validation confirming the accuracy of the model [120]. Similarly, a study by Tao et al. [123] utilized COMSOL Multiphysics-based FEM modeling, complemented with first-principles parameter inputs, to analyze the piezoelectric–semiconducting coupling in ZnO nanowires. Their results revealed how carrier screening and band structure modulation influence the piezo-gating effect, providing critical insights for energy harvesting and nanoscale sensing applications. In parallel, MATLAB has been applied to nonlinear dynamic modeling of vibration energy harvesters, where Zhang et al. [117] simulated a variable-damping mechanism for railway environments to analyze system stability, optimize harvested power, and demonstrate the feasibility of self-powered wireless sensor networks under real-world operating conditions. In addition to material and structural simulations, circuit-level analyses also feature prominently in the reviewed articles [124]. For instance, LTspice circuit simulation was used to evaluate the power management circuit (PMC) of a pulsed triboelectric nanogenerator (Pulsed-TENG). This effort led to the development of a double-loop PMC (DL-PMC), which reduces diode energy loss and enhances energy storage efficiency, showcasing how simulations can directly contribute to practical advancements in SWIoTs technologies [121]. Similarly, density functional theory (DFT)-based simulations using the VASP have been employed to model MoS_2/BP heterostructure gas sensors, which analyzed electron transfer mechanisms and band structure modulation to explain low-power, high-efficiency sensing performance, providing fundamental insights relevant to IoT-oriented self-powered devices [122].

Field experiments were attributed to 160 articles, providing empirical insights into the real-world application of CSFs for implementing SWIoTs in construction and related engineering environments. As a key validation method, these experiments involve deploying prototypes in operational settings to assess their performance under actual environmental conditions. For example, Chen et al. [125] tested a solid-liquid triboelectric nanogenerator in a high-humidity environment, demonstrating its capability to harvest mechanical energy from water mist. Similarly, Gao et al. [126] conducted a field experiment on a bridge-type shear-mode piezoelectric energy harvester, achieving significantly higher power density than conventional designs. Cho et al. [127] installed a road-compatible piezoelectric energy harvester at a highway rest area, where it successfully converted vehicular-induced mechanical energy into electrical power and maintained stable performance over several months. These studies highlight the effectiveness of field experiments in evaluating the feasibility, efficiency, and durability of SWIoTs in dynamic environments.

Additionally, theoretical models were utilized in 50 articles, indicating a vital role in conceptualizing frameworks, understanding mechanisms, and guiding experimental designs. These models bridge the gap between theory and practice, informing both laboratory experiments and simulations. For example, Mintken et al. [128] used an anharmonic oscillator model to enhance the performance of magnetostrictive-piezoelectric cantilever sensors through piezotronic amplification and resonance frequency reduction. Similarly, Chen et al. [129] combined phase-field simulations with finite element modeling to optimize core-shell textiles for coupled piezoelectric and chemoresistive sensing, advancing material innovation. In wearable technologies, Guo et al. [130] applied the Pennes equation to model heat transfer in human skin, optimizing wearable thermoelectric generators for greater thermal and electrical performance. They reported how theoretical models can provide valuable insights into sensor performance, material behavior, and energy optimization, ensuring well-informed designs that align with real-world conditions. The integration of theoretical modeling with experiments and simulations underscores a synergistic workflow in SWIoTs research, enabling rigorous testing, validation, and optimization for large-scale adoption in construction applications.

Lastly, expert evaluation was the least common method, appearing in only one study [131], indicating a limited reliance on expert judgment for assessing CSFs for implementing SWIoTs. This study combined a predesigned survey with face-to-face discussions, where experts evaluated self-powered sensor applications in C-ITS based on predefined criteria. Their assessments were quantified into data-driven scores and integrated into a T2NN VIKOR model to prioritize resilient transportation solutions.

4.5. CSFs for implementing SWIoTs in the construction industry

CSFs are key areas of activity where favorable outcomes are essential for managers to achieve their objectives [149]. They also serve as powerful project management tools for minimizing failures [150]. In the context of implementing SWIoTs in the construction industry, CSFs can be defined as the fundamental characteristics and strategic areas that drive technological advancement and efficiency [151]. In this study, the CSFs for SWIoTs encompass the key domains within construction projects that drive technological progress, enable smooth data integration, support ongoing system refinement, and enhance sensor-driven information processing. A comprehensive understanding of these CSFs is essential for researchers and industry professionals to develop strategic approaches that facilitate seamless deployment, scalability, and effectiveness of SWIoTs implementation in construction.

Fig. 3 illustrates the citation frequencies of the 28 identified CSFs across the 339 retrieved articles. Since many articles referenced multiple CSFs, the total citation count exceeds 339, reflecting the diverse research focus on different success factors. The identification of CSFs was conducted through a comprehensive full-text analysis of each article, ensuring that both explicit and implicit CSFs were identified.

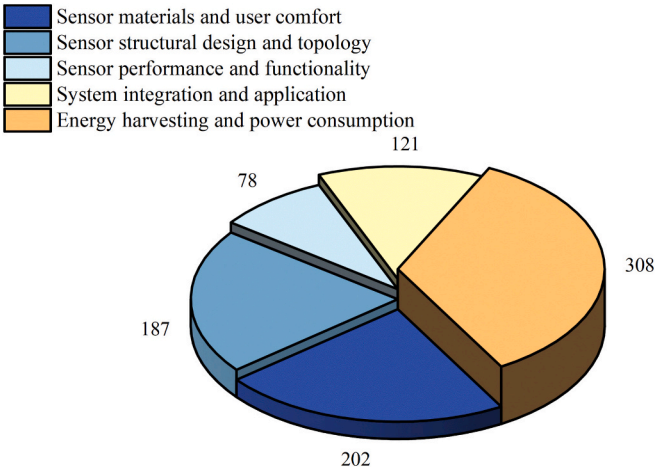

Fig. 3. Citation frequencies of 28 CSFs across 339 retrieved articles.

This meticulous approach provided a holistic assessment of the research landscape, capturing the breadth and depth of discussions surrounding the implementation of SWIoTs in construction. Table 7 categorizes the 28 identified CSFs for implementing SWIoTs in construction into five key thematic research areas. They include (1) sensor materials and user comfort, (2) sensor structural design and topology, (3) sensor performance and functionality, (4) system integration and application, and (5) energy harvesting and power consumption. The classification was established based on the underlying technological and operational aspects of each CSF, ensuring a structured and systematic framework. These thematic research areas provide a clear roadmap for future research, guiding the development of SWIoTs that are not only technologically advanced but also practical and scalable in real-world construction environments.

4.5.1. Sensor materials and user comfort

The first category, sensor materials and user comfort, underscores the importance of selecting materials that guarantee both functional performance and user adaptability. In construction applications, where sensors are exposed to harsh environmental conditions, materials must demonstrate durability and high sensitivity while addressing ergonomic risk assessment for end users.

A key aspect of sensor innovation is the use of advanced materials to enhance sensitivity and functionality [152,153]. Materials such as MXene-cellulose nanocrystal (CNC) hydrogels [196] and FeCo/Ni-clad composites [197] significantly improve sensor robustness, responsiveness, and multi-sensing capabilities. These advancements enable SWIoTs to operate more efficiently and reliably in complex applications, including structural health monitoring and dynamic sensing.

In addition to sensitivity, material durability, and stability are essential for ensuring long-term performance in harsh environments, requiring resistance to mechanical stress, extreme temperatures, and exposure to dust or moisture. Chang et al. [154] demonstrated that selenium-supported Au/Pd nanoparticles (Se/Au/Pd NPs) enhance the reliability of self-powered sensing systems due to their superior electrocatalytic properties, which improve environmental resilience. Likewise, Deng et al. [155] developed a super-stretchable triboelectric nanogenerator (SS-TENG) using a liquid conductive composite, which exhibited exceptional durability and mechanical robustness under extreme deformation. These studies highlight the role of advanced nanomaterials and structural innovations in extending sensor lifespan and ensuring stable operation under demanding conditions.

Hydrophobic surfaces play a vital role in enhancing sensor durability and reliability, particularly in humid environments. Liu et al. [160] reported that polyvinyl alcohol/lithium chloride (PVA/LiCl) films in TENGs can improve performance under high humidity by leveraging LiCl's hygroscopic properties. Their humidity-resisting TENG (HR-TENG) achieved a charge density of 244 μC/m^2 at 90 % relative humidity, more than twice the highest previously reported value (110 μC/m^2 for RH > 50 %). Additionally, at RH 90 %, the device delivered a maximum output voltage of 670 V and a current of 37 μA, showcasing superior efficiency in moisture-rich conditions. Building on this, Kim et al. [159] introduced a friction-free TENG with water-assisted oxidized aluminum electrodes, achieving 29.44 V open-circuit voltage, 204 nA short-circuit current, and 2.501 mW/m^2 peak power density at 50 MΩ load resistance. The oxidation process enhanced the effective contact area, ensuring greater output stability. Notably, the device sustained stable voltage output for over 3100 s under prolonged humidity exposure, highlighting its durability. These advancements underscore the impact of surface modifications, including hydrophobic coatings, hygroscopic materials, and oxidized electrodes, in safeguarding sensor performance and maximizing energy harvesting in harsh environments.

Ergonomic biocompatibility is a fundamental aspect of wearable sensor design, ensuring comfort, adaptability, and prolonged usability in demanding applications such as construction work [198]. Feng and Fan [158] developed a wireless self-powered breathing monitoring system utilizing a cotton belt and 3D-printed buckled structures, ensuring both biocompatibility and adaptability to body contours. Their study demonstrated that the system achieved over 90 % accuracy in respiration monitoring, even under dynamic conditions such as running and walking, highlighting its stability and comfort in real-world applications. Building on this principle, Yu et al. [199] designed a high-integration micro thermoelectric generator (μTEG) with a thin-film structure that optimizes thermal and electrical transport while minimizing bulk. Their μTEG achieved an output power density of 0.514 mW/cm^2 at a temperature difference of 33.1 K, demonstrating efficient energy harvesting without adding significant weight or rigidity to wearable systems. These advancements underscore the necessity of biocompatible materials and structurally adaptive designs in enhancing ergonomic bio-integration, improving user experience, and ensuring seamless, long-term integration of wearable sensors in physically demanding environments.

Advancements in sensitivity, durability, hydrophobicity, and biocompatibility enhance the performance and longevity of SWIoTs in construction. By integrating nanocomposites, structural reinforcements, and moisture-resistant coatings, sensors can achieve greater efficiency, resilience, and user comfort, ensuring reliable implementation on construction sites.

Table 7
Summary of related articles on CSFs for implementing SWIoTs in construction.

Category	CSFs	Code	Selected references
Sensor materials and user comfort – A	Advanced material selection for enhanced sensor sensitivity	A1	[152,153]
	Sensor material durability	A2	[154,155]
	Stability of sensor material	A3	[156,157]
	Ergonomic biocompatibility	A4	[142,158]
	Hydrophobic surface	A5	[159,160]
	Degradable and low-toxic sensor material	A6	[145,161]
	Material resilience under hygienic maintenance	A7	[162,163]
	Electrochemical self-restoration capability	A8	[137,162]
Sensor structural design and topology – B	Hyperacuity sensing topology	B1	[164,165]
	Mission-critical endurance design	B2	[154,166]
	Non-invasive sensing topology	B3	[167,168]
	Unified process framework	B4	[169,170]
	Environmental immunity matrix	B5	[116,127]
Sensor performance and functionality – C	Real-time signal acquisition and transmission	C1	[144,171]
	Embedded artificial intelligence analytics framework	C2	[172,173]
	Broad-spectrum sensing range	C3	[170,174]
	Sub-millisecond transient response	C4	[131,175]
	Autonomous sensing accuracy certification	C5	[176,177]
System integration and application – D	Miniaturization	D1	[178,179]
	End-to-end cybersecurity	D2	[131,180]
	Scalability and interoperability	D3	[181,182]
	Optimized sensor lifecycle economy	D4	[183,184]
Energy harvesting and power consumption – E	Low power consumption	E1	[175,185]
	Sensor energy conversion yield	E2	[186,187]
	Autonomous multi-source energy integration	E3	[188,189]
	Mission-critical energy orchestration	E4	[190,191]
	Flexible self-power generator and energy storage technology	E5	[192,193]
	Sub-threshold energy activation mechanism	E6	[194,195]

4.5.2. Sensor structural design and topology

The second category, sensor structural design and topology, focuses on optimizing the architecture and configuration of SWIoTs to meet the demands of construction applications. Structural design plays a pivotal role in ensuring sensors are not only robust and adaptable but also capable of delivering reliable data in diverse and challenging environments on construction sites.

One critical aspect of sensor design is the development of hyperacuity sensing topology, which enhances spatial resolution and precision through advanced geometric arrangements of sensor arrays. Han et al. [164] introduced a flexible piezoelectric acoustic sensor inspired by the basilar membrane, utilizing multi-channel resonant frequencies to achieve 4–8 times higher sensitivity than conventional condenser sensors. This design enabled the precise detection of acoustic stimuli with displacements as small as 10 nm, demonstrating its potential for high-precision sensing applications. On the other hand, Yi et al. [165] developed a piezoelectric force sensor based on thinned bulk PZT, significantly improving strain distribution uniformity and detection sensitivity. With a sensitivity of approximately 10 V/N, notably higher than conventional deposited PZT film-based sensors, this design allows precise detection of micro-level structural deformations. Its high resolution makes it particularly valuable for real-time monitoring of arterial pulse signals, where recorded voltage amplitudes for radial artery pulse detection reached 180 mV, nearly double previous reports.

The concept of non-invasive sensing topology emphasizes the design of sensors that operate effectively without compromising the structural integrity of their monitored environments. For instance, Verma et al. [168] developed hybrid architectures for structural health monitoring (SHM), utilizing capacitive interfaces with approximately 100 pF/cm^2 capacitance and inductive coupling capable of non-contact signal transfer over large areas. This allowed centimeter-scale sensor density to detect strain changes critical for SHM while avoiding invasive sensor installation processes. Bhatia et al. [167] studied the importance of this approach through wearable TENGs for upper-limb rehabilitation. The TENGs generated up to 4 V open-circuit voltage and 200 nA current, enabling real-time motion tracking and energy harvesting without requiring intrusive modifications, thus preserving the user's physical comfort and mobility. These innovations illustrate how non-invasive sensing preserves structural integrity while enabling high-density sensor deployment, ensuring reliable performance, extended operational lifespan, and adaptability to diverse environments.

To further enhance reliability, the environmental immunity matrix design focuses on improving sensor resilience under harsh conditions [116]. For example, the omnidirectional wind-based triboelectric generator (OW-TEG) incorporates a symmetric circular structure and optimized control circuits to mitigate electromagnetic interference, achieving a uniform output performance across 360° wind directions with a sensitivity of 50.2 Hz/m/s for wind speeds between 11.3 and 16.8 m/s [200]. Likewise, the road-compatible piezoelectric energy harvester (RPEH) employs dual-end fixed piezoelectric transducers and polyurethane encapsulation to resist mechanical stress and moisture ingress, generating a maximum power of 2080 mW at 30 km/h and maintaining stable operation under 149,840 vehicle passes over five months, with internal temperature variations limited to 0.35 °C [127]. These strategies collectively strengthen electromagnetic stability, waterproofing, and thermal resilience, enabling long-term operation in demanding environments.

By systematically addressing structural optimization, non-invasive sensing, and environmental immunity, SWIoTs achieve enhanced durability, precision, and adaptability, making them well-suited for real-world construction applications.

4.5.3. Sensor performance and functionality

The third category, sensor performance and functionality, defines the core capabilities that enable SWIoTs to meet the rigorous demands of construction applications. High-performance sensors must integrate precision, responsiveness, and intelligent data processing to deliver real-time, actionable insights.

A critical factor in this domain is real-time signal acquisition and transmission, allowing sensors to detect, process, and relay data instantaneously. Yi et al. [165] developed a piezoelectric force sensor for arterial pulse monitoring, combining high sensitivity with efficient wireless transmission to enable rapid responses in healthcare and human-machine interactions. Zhao et al. [171] demonstrated a TENGs that enables real-time wireless monitoring of cardiovascular activities with heart rate detection accuracy reaching 99.73 % and the capability to transmit complete pulse waveforms to mobile devices, critical for immediate diagnostics and intervention in medical settings. Zhu et al. [144] showcased a shaftless turbine flow sensor (STIFS) that achieves a real-time signal frequency sensitivity of 0.71 Hz/L min^{-1} across airflow ranges of 300–900 L/min, while generating 374 V to power data processing and wireless transmission modules, ensuring complete self-sufficiency for real-time industrial monitoring These breakthroughs underscore how cutting-edge sensing technologies drive instantaneous data acquisition, improving operational efficiency and safety in dynamic environments.

Embedded artificial intelligence (AI) analytics frameworks are increasingly integrated into wearable and self-powered sensor systems, enabling real-time data processing and decision-making at the edge without reliance on centralized systems [172]. This autonomous data processing capability reduces latency, conserves power, and enhances predictive maintenance and resource management. In graphene textile TENGs, machine learning algorithms process sensing signals to classify four standardized human motions, including slow walking, fast walking, slow running, and fast running, with high precision, achieving an average classification accuracy of 95.3 % [173]. Triboelectric sensors integrated into an intelligent neck ring system identify different neck movements with a peak recognition accuracy of 96.10 %, improving real-time driver status monitoring [152]. Flexible electret-based pressure sensors utilize AI-driven classification techniques to diagnose respiratory diseases, reaching 99.43 % accuracy, 98.30 % sensitivity, and 99.02 % specificity [142]. These implementations demonstrate how embedded AI analytics can enhance adaptability, efficiency, and intelligence in next-generation SWIoTs.

By advancing real-time sensing, intelligent analytics, and seamless integration, sensors could achieve the speed, precision, and autonomy required for next-generation construction applications. These innovations not only elevate functionality but also strengthen interoperability with smart technologies, driving the evolution of the construction industry.

4.5.4. System integration and application

The fourth category, system integration and application, focuses on the seamless incorporation of SWIoTs into construction workflows, ensuring they operate efficiently and reliably across diverse systems. Successful implementation depends on addressing critical aspects such as miniaturization, interoperability, and cost-effectiveness.

Miniaturization is essential for enhancing sensor functionality while reducing the physical footprint and enabling seamless integration into various systems. In energy harvesting applications, compact piezoelectric sensors retain high efficiency despite size reductions. A case in point is ferroelectret polypropylene-based piezoelectric harvesters, which demonstrated that even with a smaller form factor, these devices achieved an output power density of up to 39 $\mu W/g/mm^3$ under an acceleration of 9.81 m/s^2, making them highly suitable for space-constrained environments [178]. Advancements in this direction were already evident in earlier work. TENGs have benefited significantly from miniaturization, as seen in a solid-liquid contact TENG that, despite its small and lightweight structure, generated a high open-circuit voltage of 70 V and a short-circuit current of 2.4 mA at just 2 Hz, demonstrating the feasibility of compact designs in low-frequency environments [179]. More recently, researchers have further refined structural configurations

and streamlined circuitry to shrink device dimensions without sacrificing performance, as exemplified by multi-output AC/DC TENGs for self-powered sensors, which achieved peak instantaneous DC and AC power outputs of 1.05 μW and 1.12 μW, respectively, across a 7 MΩ resistance while maintaining a minimal footprint [120]. Collectively, these innovations demonstrate how miniaturization continues to drive sensor technology forward, particularly in applications requiring compact yet high-performance solutions.

End-to-end cybersecurity is critical for ensuring the resilience and reliability of SWIoTs networks in construction environments, where interconnected smart sensors facilitate real-time monitoring and data-driven decision-making. Research emphasizes that implementing robust encryption, secure authentication protocols, and decentralized data management effectively mitigates risks associated with unauthorized access and data breaches [131,180]. Xiong et al. [180] demonstrated that self-powered wireless sensors experience a decline in reliability due to environmental stressors, with an operational status evaluation revealing an output power stability deviation of up to 23.26 %, making cybersecurity measures essential to prevent data manipulation and loss. Blockchain-based security frameworks further enhance system integrity by providing tamper-proof records of sensor data, improving transparency and trust in construction workflows [182]. Furthermore, AI-driven cybersecurity mechanisms can analyze cybersecurity risks in cooperative intelligent transportation systems (C-ITS) using a type-2 neutrosophic fuzzy VIKOR model, showing that inadequate cybersecurity could result in significant disruptions, with security-related criteria such as data integrity and secure communication ranking among the top priorities in decision-making. [131]. As self-powered sensors are increasingly deployed in critical infrastructure, ensuring resilience against cyber threats requires a holistic approach that combines advanced cryptographic methods, secure communication protocols, and continuous monitoring of vulnerabilities. These measures collectively reinforce the security and stability of SWIoTs, ensuring robust protection in smart construction environments.

By addressing these critical factors, system integration and application ensure that SWIoTs can function effectively within construction ecosystems, promoting reliability, efficiency, and long-term sustainability.

4.5.5. Energy harvesting and power consumption

The fifth category, energy harvesting and power consumption, focuses on developing efficient energy management systems to sustain SWIoTs in construction applications. In challenging environments where a continuous power supply is critical, optimizing energy harvesting and consumption is essential to extend sensor lifespan and reduce maintenance demands.

Sensor energy conversion yield, a crucial metric in energy harvesting, defines the efficiency of converting ambient energy, such as mechanical vibrations, thermal gradients, or solar radiation, into electrical power. Advances in this field have significantly enhanced conversion efficiency, paving the way for autonomous sensor operation across diverse environments [186,187]. A study designed a double-loop power management circuit for triboelectric nanogenerators, achieving an optimal energy storage efficiency of 48.9 % at low operating voltages, an essential advancement for self-powered sensing systems [121]. Meanwhile, Guo et al. [130] quantified the energy conversion efficiency of a wearable annular thermoelectric generator (WATEG), revealing key performance factors. Blood perfusion significantly enhanced conversion, while metabolic heat had a negligible impact. Optimizing the load resistance to 1.467 times the internal resistance improved energy transfer. Using PDMS (Polydimethylsiloxane) as the fill material, the WATEG achieved a peak power density of 26.97 $\mu W/cm^2$ at an optimal fill factor of 0.1599. Increasing the thermoelectric leg height to 97.37 % of the total WATEG height and applying 0.5 kPa contact pressure further improved conversion efficiency by reducing thermal resistance. Furthermore, Zhuo et al. [112] introduced a hybrid energy harvester integrating piezoelectric and electromagnetic mechanisms, effectively overcoming low-amplitude vibrations in high-speed railway environments and delivering a 250 % higher power output than conventional designs. These innovations collectively emphasize the necessity of optimizing energy conversion yield to enable sustainable and efficient sensor networks in dynamic settings.

Another key factor is the integration of autonomous multi-source energy harvesting, which combines energy from multiple sources to enhance reliability. Hybrid energy systems that combine multiple energy harvesting sources, such as solar, mechanical, and thermal energies, offer reliable and stable energy supplies for SWIoTs in fluctuating environmental conditions at construction sites. Qiao et al. [188] demonstrated that heterogeneous sources, including corrosion energy, cement-based batteries, and weak solar panels, successfully charged a supercapacitor to 2.3 V in approximately 2500 s, ensuring the sustained operation of wireless corrosion-monitoring sensors. Expanding on this concept, Yang and Wang [189] reported that hybrid energy cells combining piezoelectric, pyroelectric, and solar nanogenerators achieved an open-circuit voltage of up to 5.2 V and a current of 34 mA under simultaneous light, thermal, and mechanical inputs. These developments underscore the potential of multi-source energy harvesting systems as sustainable energy solutions for a wide range of applications.

Flexible self-powered generators, particularly TENGs and TEGs, are further transforming energy harvesting by enabling seamless integration into lightweight, adaptable devices. Lu et al. [192] developed a stretchable and transparent triboelectric nanogenerator (PL-TENG) utilizing a polyacrylamide-lithium chloride hydrogel and polydimethylsiloxane, which exhibited a stretchability of up to 300 % strain while maintaining stable electrical output. The device also retained its performance after 10,000 mechanical cycles, demonstrating excellent durability under repeated deformations. Yuan et al. [193] further enhanced flexibility in a Kevlar-based TENG, which combined shear-stiffening gel and carbon nanotubes to provide mechanical adaptability. This design allowed the device to endure high-impact forces while functioning as a self-powered wearable sensor, ensuring both flexibility and robustness under dynamic conditions. Advancing the field, Zhang et al. [181] developed a flexible micro thermoelectric generator (FTEG) with a lightweight polyimide substrate, achieving an ultrathin and bendable structure that maintained a power factor of 16.0 $\mu W\ cm^{-2}\ K^{-2}$ even when bent to a radius of 13 mm. The device demonstrated no significant change in internal resistance when subjected to various bending curvatures, confirming its high mechanical flexibility. These breakthroughs demonstrate the role of advanced materials and nanostructured composites in enhancing the efficiency, durability, and adaptability of flexible self-powered generators for next-generation wearables.

By prioritizing energy conversion efficiency, multi-source harvesting, and flexible self-powered technologies, SWIoTs could achieve greater autonomy, durability, and seamless operation in complex construction environments, paving the way for self-sustaining, intelligent sensing systems.

5. Discussion

5.1. Conceptual framework of CSFs for implementing SWIoTs in construction

The adoption and successful implementation of SWIoTs in construction depends on an intricate system of CSFs that do not function in isolation but rather interact dynamically, forming reinforcing and balancing feedback loops. Understanding these interdependencies is essential for optimizing sensor design, integration, and long-term feasibility in construction environments. Since CSFs in practice typically range between five and ten [201], recognizing their complementary nature allows for effective resource allocation, thereby enabling enhanced performance, cost-effectiveness, and broader industry

adoption [150]. The framework also highlights key interactive result areas, which can be prioritized to maximize the synergistic benefits of CSFs, ultimately advancing the integration of SWIoTs in construction projects.

To capture these systemic interactions, two interrelated causal loop frameworks have been developed. Fig. 4 presents a high-level classification-based loop conceptual framework that organizes CSFs into the five thematic research areas. Building upon this framework, Fig. 5 refines the framework by mapping out the micro-level interactions between specific CSFs within each classification, revealing how detailed design decisions influence broader system behavior.

5.1.1. Reinforcing feedback loops in the classification-based conceptual framework

The classification-based loop conceptual framework illustrates a reinforcing cycle in which improvements in one category cascade into others, as shown in Fig. 4, generating a continuous loop of technological enhancement. As sensor materials become more advanced, they facilitate improvements in structural design, which in turn enhances sensor performance and functionality. These advancements enable more effective system integration, ensuring smoother adoption within construction workflows. A well-integrated system further supports energy efficiency and optimized power consumption, allowing sensors to operate autonomously with minimal maintenance. This, in turn, provides greater flexibility for further refinements in sensor performance, reinforcing the continuous cycle of improvement.

Beyond this primary reinforcing mechanism, the classification-based framework also reveals cross-category dependencies. Sensor materials influence system integration because material selection determines miniaturization and compatibility with wearable designs. Similarly, structural design plays a crucial role in energy harvesting, as different sensor topologies enable varying levels of power capture efficiency. Performance requirements drive material innovations as new sensing functionalities demand materials with enhanced properties such as flexibility, conductivity, or self-healing capabilities. The recursive nature of these relationships means that incremental advancements in one area generate compounding improvements throughout the system, reinforcing the value of a holistic, multi-faceted approach to SWIoTs development.

5.1.2. CSF-based loop conceptual framework: micro-level interdependencies

The CSF-based loop conceptual framework in Fig. 5 highlights the interdependencies shaping SWIoTs performance in construction. Key drivers such as sensor energy conversion yield (E2), embedded AI analytics (C2), and miniaturization (D1) optimize system functionality. Additionally, the synergy between hydrophobic surfaces (A5) and material resilience under hygienic maintenance (A7) enhances durability and user comfort, reinforcing adaptability.

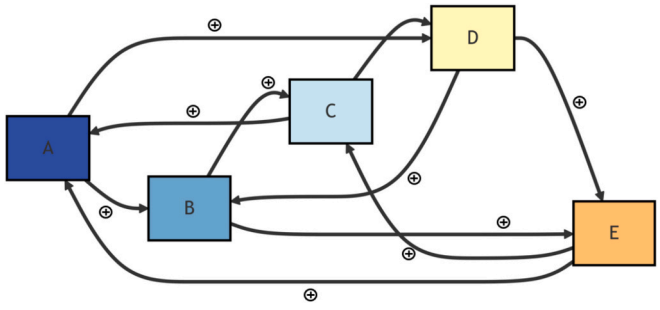

Fig. 4. Classification-based loop conceptual framework of CSFs for implementing SWIoTs in construction.
Note: A = Sensor materials and user comfort; B = Sensor structural design and topology; C = Sensor performance and functionality; D = System integration and application; E = Energy harvesting and power consumption.

The primary loop begins with advanced material selection (A1), which enhances sensor sensitivity and hyperacuity sensing topology (B1), strengthening real-time signal acquisition (C1). This facilitates high-speed data transmission, supporting scalability (D3) and seamless integration across diverse environments. Energy conversion yield (E2) sustains core functions, including electrochemical self-restoration (A8) and AI-driven processing (C2). In turn, C2 bolsters cybersecurity (D2) and drives material innovation (A1), ensuring AI-compatible sensor advancements. Beyond the primary loop, cross-category relationships further enhance system functionality. Ergonomic biocompatibility (A4) supports miniaturization (D1), while mission-critical endurance (B2) stabilizes power distribution (E4). E2 strengthens self-restoration (A8), and AI analytics (C2) refine material selection (A1). Sub-threshold energy activation (E6) accelerates transient response (C4), ensuring rapid, low-power operation. These interdependencies collectively enhance SWIoTs by improving autonomy, resilience, and efficiency. Through optimized material selection, energy management, and AI-driven analytics, SWIoTs achieve seamless integration across diverse construction environments while ensuring long-term sustainability and adaptability to evolving technological demands.

5.1.3. Strategic implications for SWIoTs optimization in construction

Integrating classification-based and CSF-based loop frameworks reveals key strategies for optimizing SWIoTs in construction. Reinforcing balanced feedback loops emphasizes the need to leverage synergies while managing trade-offs to ensure performance and sustainability. A core strategy is optimizing power management, data processing, and compact design. Sensor energy conversion yield (E2) sustains self-restoration (A8) and AI-driven analytics (C2), which enhance cybersecurity (D2) and predictive capabilities. Miniaturization (D1), influenced by broad-spectrum sensing (C3) and sub-millisecond response (C4), improves sensor integration while maintaining low power consumption (E1), ensuring efficiency without compromising performance. Material innovation must balance durability and adaptability. Hydrophobic surfaces (A5) extend sensor lifespan, while material resilience under hygienic maintenance (A7) enhances comfort and usability, supporting long-term deployment. However, trade-offs exist, which enhanced material durability (A2) may reduce ergonomic biocompatibility (A4), requiring hybrid materials. Broad-spectrum sensing (C3) increases adaptability but adds processing complexity, affecting response times (C4) and necessitating edge computing advancements. Strengthened cybersecurity (D2) protects data but raises computational and energy costs (D4), demanding efficient encryption solutions. By strategically reinforcing synergies and mitigating constraints, SWIoTs can achieve enhanced efficiency, resilience, and adaptability. A holistic approach integrating power optimization, AI-driven sensing, and advanced materials will ensure SWIoTs remain viable for real-world construction applications.

5.2. Potential and existing implications of CSFs for implementing SWIoTs in construction

The integration of SWIoTs into construction environments is transforming how structural integrity, worker safety, and equipment maintenance are managed. Unlike conventional IoT systems that rely on external power sources, SWIoTs offer continuous, real-time monitoring, enabling predictive analytics, AI-driven decision-making, and resource-efficient operations. Their self-sustaining nature makes them critical in advancing smart, interconnected construction ecosystems. Rather than functioning solely as passive monitoring tools, SWIoTs actively contribute to proactive risk mitigation and efficiency optimization. By leveraging adaptive energy harvesting, AI-powered analytics, and automated sensing technologies, they enhance construction workflows, predictive maintenance, and worker-centric safety solutions. The following sections highlight key applications of SWIoTs in SHM, worker safety, machinery health monitoring, and how identified CSFs would

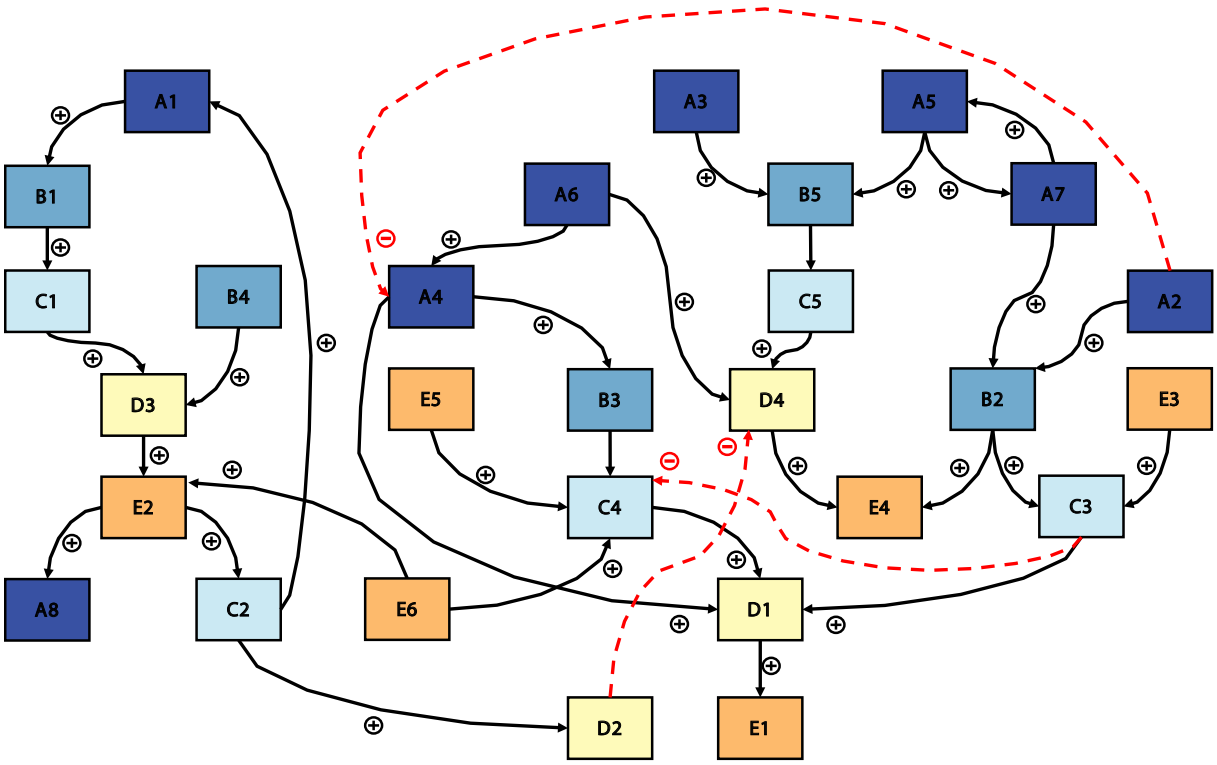

Fig. 5. CSF-based loop conceptual framework for implementing SWIoTs in construction.

play a crucial role, demonstrating their transformative impact on next-generation construction technologies.

5.2.1. *Structural health monitoring (SHM)*

SHM is indispensable for safeguarding the integrity and longevity of construction projects, forming a cornerstone of smart city infrastructure. Conventional SHM methods, which depend on wired sensor networks and periodic manual inspections, often result in delayed fault detection and escalating maintenance expenses. In contrast, SWIoTs revolutionize this process by enabling real-time, self-sustaining monitoring, continuously assessing structural stress, deformation, and environmental influences. By seamlessly integrating AI-driven predictive analytics with energy-harvesting capabilities, these systems preemptively identify potential failures, optimize maintenance efficiency, and bolster structural resilience. As outlined in Table 8, the successful implementation of autonomous SHM systems hinges on several CSFs. By embedding key CSFs such as real-time signal acquisition and transmission, embedded AI analytics framework, and optimized sensor lifecycle economy, SWIoTs facilitate a paradigm shift toward proactive, cost-effective infrastructure monitoring, accelerating the evolution of intelligent construction.

5.2.2. *Worker safety and human-centric monitoring*

Construction workers face significant risks from fatigue, hazardous materials, and environmental conditions. Traditional safety measures, such as manual check-ins and infrequent monitoring, fail to enable real-time intervention, increasing accident risks. SWIoTs embedded in personal protective equipment (PPE), including helmets, vests, and masks, provide continuous health monitoring by tracking vitals, posture, and exposure to hazardous conditions. By integrating real-time alerts and self-powered operation, these devices facilitate proactive risk mitigation and rapid emergency response. As shown in Table 9, the successful deployment of SWIoT-based worker safety systems relies on key CSFs that ensure reliable, secure, and efficient health monitoring in dynamic construction environments. Incorporating CSFs such as ergonomic biocompatibility, environmental immunity matrix, and broad-spectrum

Table 8
CSFs for continuous and self-powered SHM.

Key benefits and applications	Corresponding CSFs	Role in adopting SWIoTs in construction
Real-time detection of stress variations and early-stage material degradation using TENGs and piezoelectric sensors.	Real-time signal acquisition and transmission	SWIoTs must capture instantaneous stress variations to prevent undetected structural damage, enabling immediate intervention and reducing failure risks.
AI-integrated SHM systems that differentiate transient load fluctuations from structural damage to improve failure prediction [202].	Embedded AI analytics framework	AI-driven SWIoTs analyze stress patterns in real-time, filtering out false alarms and ensuring only critical issues trigger maintenance responses, optimizing resources.
Use of nanostructured thermoelectric composites (e.g., CNT-reinforced cement) to enable autonomous energy harvesting for continuous operation [203].	Autonomous multi-source energy integration	Allows permanent sensor deployment in infrastructure without requiring external power or battery replacement, ensuring continuous structural monitoring.
Reduction in maintenance costs and enhancement of infrastructure resilience through automated risk assessments.	Optimized sensor lifecycle economy	By minimizing sensor replacements and enabling long-term operation, SWIoTs reduce monitoring costs while enhancing structural longevity.
Hydrogel-based TENGs embedded in bridges and high-rises provide long-term structural diagnostics, ensuring timely intervention and extended infrastructure lifespan [204].	Environmental immunity matrix	Ensure sensors remain operational under extreme weather conditions, providing long-term structural monitoring without degradation.

Table 9
CSFs for worker safety and human-centric monitoring.

Key benefits and applications	Corresponding CSFs	Role in adopting SWIoTs in construction
Continuous monitoring of worker fatigue and injury risks using hydrogel-based strain sensors [205].	Ergonomic biocompatibility	SWIoTs must be lightweight, flexible, and non-intrusive, ensuring workers wear them comfortably for extended periods without reducing productivity.
Detection of hazardous gas exposure and respiratory distress through flexoelectric bending sensors in masks [206].	Environmental immunity matrix	Sensors must function reliably in dusty, humid, and high-temperature environments, ensuring uninterrupted respiratory monitoring in extreme conditions.
Prevention of posture-related accidents using wearable triboelectric sensors that track worker movement and fatigue [152].	Broad-spectrum sensing range	SWIoTs must monitor multiple physiological parameters (heart rate, movement, hydration levels) to provide comprehensive safety tracking and prevent injuries.
AI-driven safety alerts enable real-time interventions and reduce workplace accidents.	End-to-end cybersecurity	Worker health data is highly sensitive, requiring secure, encrypted real-time communication to protect privacy while ensuring immediate alerts for supervisors.

sensing range, SWIoTs significantly enhance worker safety, prevent accidents, and ensure compliance with health regulations.

5.2.3. Real-time machinery health monitoring

Heavy machinery breakdowns in construction lead to costly delays, safety risks, and operational inefficiencies. Traditional scheduled maintenance fails to detect real-time wear and tear. SWIoTs, embedded in machinery components, continuously monitor vibration patterns, temperature fluctuations, and stress levels. Leveraging self-powered operation and AI-driven diagnostics, these sensors enable predictive maintenance, reducing downtime and extending equipment lifespan. As shown in Table 10, the successful adoption of SWIoTs for real-time machinery monitoring depends on key CSFs that enhance fault detection accuracy, energy efficiency, and durability in rugged construction environments. By shifting from reactive maintenance to predictive monitoring, SWIoTs minimize downtime, prevent catastrophic failures, and optimize maintenance costs.

Table 10
CSFs for predictive maintenance and energy-harvesting machinery monitoring.

Key benefits and applications	Corresponding CSFs	Role in adopting SWIoTs in construction
Continuous detection of abnormal stress and wear in cranes, excavators, and concrete mixers using self-powered vibration sensors [108].	Sensor energy conversion yield	SWIoTs must harvest mechanical vibrations into usable power, ensuring continuous monitoring without reliance on external power sources.
AI-powered diagnostics to predict mechanical failures, including gear misalignment and bearing wear [207].	Autonomous sensing accuracy certification	SWIoTs must provide highly accurate fault detection, preventing unnecessary maintenance while ensuring timely interventions for actual risks.
A DL-TENG vibration sensor on crane motors harvests mechanical energy while detecting early-stage misalignments [108].	Real-time signal acquisition and transmission	Ensures that early-stage mechanical failures are detected before they escalate, allowing for timely maintenance and minimized operational disruptions.

5.3. Research gaps and future research directions of CSFs for implementing SWIoTs in construction

5.3.1. Optimizing SWIoT sensor materials for biomechanical, environment-resilience, and self-healing

The success of SWIoTs in construction largely depends on the properties of sensor materials, which directly impact wearability, durability, and long-term performance. A key category of CSFs in SWIoTs adoption is ***Sensor Material and User Comfort***, highlighting the need for flexible, breathable materials that maintain structural integrity under continuous wear.

While existing research has focused primarily on enhancing sensor sensitivity and energy efficiency, a critical gap remains in the development of highly adaptable, user-friendly materials for construction environments. Stiff, impermeable materials can cause discomfort, reduce sensor adhesion, and limit long-term usability, ultimately lowering compliance rates. Future research should prioritize biocompatible, durable, and self-healing sensor materials to enable continuous, real-time monitoring without compromising worker comfort or safety. Several critical research questions remain to be explored:

a. *How can SWIoTs materials be designed to enhance both wearability and biomechanical adaptability in construction environments?*

- **Precision-driven customization for biomechanical adaptation**: A major challenge in SWIoT adoption for construction safety is the limited biomechanical adaptability of current sensor materials [208,209]. Conventional wearable IoT devices often fail to accommodate individual variations in body structure, leading to discomfort and reduced sensor accuracy [146,210–212]. Without precise adaptation to body movements and dynamic stress points, sensor placement can shift during use, causing data inconsistencies and reducing reliability. To sum up, where workers perform physically demanding tasks in hazardous environments, poorly fitted wearables can hinder performance, limit adoption, and compromise safety monitoring [46,213,214]. Future research should explore multi-material 3D printing and computational modeling to develop ergonomically optimized SWIoTs that conform precisely to an individual's biomechanics, enhancing both comfort and data reliability. Parametric modeling techniques could enable real-time design adjustments based on user-specific factors such as body dynamics, posture, and motion patterns, ensuring seamless integration into diverse construction workflows. Additionally, adaptive designs tailored to PPE and construction attire could enhance long-term usability, sensor accuracy, and worker compliance. These advancements would ultimately improve safety monitoring, productivity assessment, and health surveillance in complex construction environments.

b. *How can advanced materials and structural adaptations enhance the durability and reliability of SWIoTs in extreme construction environments?*

- **Environmental sensing resilience-based SWIoTs**: Ensuring the durability and reliability of sensors in extreme environmental conditions is critical for SWIoTs deployed in construction. High temperatures, particularly in outdoor sites, high-rise structures, and industrial facilities, can degrade sensor performance [215–219]. Future research should explore nanocomposite-based substrates incorporating ceramic or graphene derivatives to enhance electrical conductivity and mechanical stability under heat stress. Additionally, thermal barrier coatings, such as aerogels or metal oxide layers, could shield sensitive components from excessive heat, ensuring

long-term functionality in sun-exposed environments. Beyond temperature resilience, strong winds introduce mechanical challenges, including vibration, signal disruption, and structural fatigue in sensors deployed on cranes, scaffolding, and smart façades [220–223]. To address these issues, future studies should investigate biomimetic aerodynamic designs inspired by owl wings or plant leaves to reduce wind-induced noise and drag, thereby improving sensor stability. The integration of vibration-damping coatings and flexible structural adaptations could further enhance reliability, ensuring uninterrupted data collection for real-time SHM and construction safety applications.

c. *How can SWIoTs be designed to enhance corrosion resistance and ensure long-term reliability in harsh construction environments?*

- **Self-Healing and corrosion resistance for SWIoTs in construction**: Exposure to moisture, chemicals, and corrosive agents in construction environments can significantly degrade sensor performance and longevity [140,161,224,225]. To mitigate these effects, future research should explore self-healing polymer coatings and hydrophobic nanofilms capable of autonomously repairing surface defects, ensuring long-term reliability in harsh conditions such as bridges, tunnels, and high-humidity worksites. In the short to medium term (approximately 3–7 years), research may emphasize laboratory-scale synthesis and validation of these coatings, while longer-term efforts (7–12 years) could focus on durability testing and field implementation. Additionally, integrating graphene oxide and superhydrophobic nanostructures into sensor surfaces could enhance corrosion resistance, improving the resilience of SWIoTs in marine infrastructure, underground construction, and industrial facilities [226,227]. These advancements would extend sensor lifespan, reduce maintenance demands, and enhance long-term data reliability in demanding construction environments. However, realizing such material innovations is not without barriers. Technically, challenges remain in scaling up advanced composites and self-healing coatings for mass production, as well as validating their durability under prolonged, real-world construction conditions. Economically, the high costs of novel nanomaterials and multi-material fabrication may limit adoption, particularly in resource-constrained projects where affordability and ease of replacement are critical. Addressing these barriers would be essential to translate material-level innovations into practical, field-ready SWIoTs solutions.

5.3.2. *Mission-critical energy harvesting for resilient building energy systems*

Achieving mission-critical energy autonomy in large-scale building infrastructures depends on the efficiency of energy harvesting systems, which directly impact reliability, scalability, and long-term performance. A key category of CSFs in energy-harvesting SWIoTs is ***Energy Harvesting and Power Consumption***, emphasizing the need for efficient energy conversion, adaptive storage mechanisms, and seamless integration with existing Building Energy Management Systems. While existing research has primarily focused on improving energy efficiency and storage capacity, a critical gap remains in the development of highly integrated, self-sustaining energy ecosystems for smart buildings. Conventional grid-dependent systems are prone to power outages, energy losses, and high maintenance costs, limiting their long-term viability. Inefficient energy harvesting and distribution can disrupt critical operations, increase dependency on external power sources, and reduce overall system resilience. Future research should prioritize hybrid energy harvesting, real-time optimization, and dynamic power distribution to establish fully autonomous, self-powered smart buildings. Several critical research questions remain to be explored:

a. *How can SWIoTs be implemented for large-scale self-powered smart sensing buildings?*

- **SWIoTs are transforming large-scale smart buildings:** The integration of SWIoTs within large smart buildings is transforming energy management, environmental monitoring, and predictive maintenance by enabling continuous, real-time data collection without reliance on external power sources [228,229]. One of the most effective methods of energy harvesting in smart buildings is photovoltaic (PV) integration, where thin-film solar cells are embedded into windows, facades, skylights, and rooftops to generate electricity from natural and artificial light sources [230]. Unlike traditional rooftop solar panels, semi-transparent perovskite PV films can be directly applied to glass surfaces, capturing sunlight while maintaining visibility and aesthetic appeal [231]. These PV-integrated surfaces can power sensor nodes distributed throughout the building, supporting real-time indoor air quality monitoring, occupancy detection, and climate control systems. Additionally, PV surfaces integrated into HVAC ducting and ventilation shafts can provide a localized power source for embedded airflow sensors, optimizing heating, cooling, and air circulation efficiency based on real-time environmental data. Beyond solar energy, TEGs play a crucial role in harnessing temperature gradients within buildings. TEGs can be strategically placed on radiators, heated flooring, ventilation ducts, and even hot water pipes to convert thermal energy into electricity. In high-traffic commercial buildings, where HVAC systems account for a significant portion of energy consumption, self-powered TEG sensors can continuously monitor temperature distribution, heat loss, and system efficiency, enabling predictive maintenance and automated climate control adjustments. For instance, TEG-powered sensors embedded in insulation materials can detect areas of heat leakage, informing real-time insulation optimization strategies to reduce energy waste. Similarly, in server rooms or high-density office spaces where cooling demands are high, self-powered thermal sensors can adjust airflow patterns and cooling intensity based on localized temperature data, reducing unnecessary energy expenditure.

  PENGs and TENGs offer additional avenues for energy harvesting by capturing mechanical vibrations and human-induced motion within the building environment. PENGs can be integrated into flooring systems, staircases, and structural beams, generating electricity from foot traffic, mechanical stress, and building vibrations caused by wind or external forces. These self-powered sensors can monitor structural integrity in high-rise buildings, detecting micro-deformations, stress accumulation, and vibration anomalies that could indicate potential faults. In commercial and public spaces such as airports, shopping malls, and office complexes, TENG-powered sensors embedded in elevator shafts, escalators, and revolving doors can capture energy from repetitive mechanical movements, ensuring the continuous operation of occupancy sensors, lighting controls, and security systems.

b. *How can SWIoTs dynamically optimize energy consumption in mission-critical applications?*

- **AI-driven energy optimization for mission-critical facilities:** Energy harvesting alone is insufficient to ensure uninterrupted power in mission-critical facilities such as hospitals, research laboratories, and emergency shelters [232]. These environments require real-time energy optimization mechanisms that can predict demand fluctuations, prioritize power distribution, and regulate energy-intensive operations such as air circulation, HVAC, and emergency lighting [233,234]. Future research should focus on integrating SWIoTs with AI-driven predictive energy management systems capable of dynamically adjusting power distribution based on real-time occupancy, environmental conditions, and historical

consumption patterns. In the near term (2–4 years), efforts are likely to focus on algorithm development and small-scale pilot implementations within controlled construction settings. In the medium term (5–8 years), such systems could be scaled to complex, multi-site projects, enabling robust integration with heterogeneous SWIoTs networks and demonstrating practical value for large-scale construction operations. For example, temperature and humidity sensors linked to TENGs should continuously monitor HVAC efficiency and adjust energy allocation accordingly, ensuring minimal power waste. Similarly, occupancy-detection SWIoTs embedded in hospital patient rooms or school lecture halls should enable demand-responsive lighting and air circulation, reducing unnecessary energy consumption during low-occupancy periods. AI-based optimization algorithms should also be developed to assess how harvested energy can be dynamically redirected across the building. For instance, surplus power from solar-integrated facades during peak daylight hours could be stored in supercapacitors or lithium-ion batteries and later redistributed to areas with higher energy demands, such as emergency medical units. To ensure practical implementation, experimental testing of these adaptive energy optimization frameworks should be conducted in various facility types, quantifying their impact on overall energy efficiency, operational cost reductions, and system resilience. Nonetheless, realizing mission-critical, self-powered energy systems faces several barriers. From a technical perspective, challenges include ensuring reliable hybrid integration of multiple energy harvesters, managing variability in energy supply, and guaranteeing continuous operation in unpredictable environments. Economically, high upfront costs for integrating advanced materials, storage devices, and AI-driven management platforms may limit adoption in resource-constrained facilities. Overcoming these barriers would be essential to establish resilient, fully autonomous energy ecosystems for smart buildings.

5.3.3. *Architecture-agnostic expansion for scalable and interoperable SWIoTs systems*

The successful integration of SWIoTs into diverse construction environments depends on their scalability and interoperability across multiple architectural frameworks. A critical category of CSFs in SWIoTs adoption is ***System Integration and Application***, which underscores the need for seamless communication, compatibility, and data exchange between edge devices, cloud platforms, and legacy monitoring systems. While existing research has primarily focused on improving sensor performance and network efficiency, significant challenges persist in ensuring SWIoTs interoperability within heterogeneous construction ecosystems. Rigid, architecture-dependent frameworks can impede large-scale deployment, restrict cross-platform functionality, and reduce adaptability to evolving industrial demands. To address these limitations, future research should prioritize architecture-agnostic, modular frameworks that support reliable, scalable, and real-time SWIoTss operations across diverse network infrastructures. Several critical research questions warrant further investigation:

a. *How can modular sensor integration frameworks and standardized communication protocols enhance SWIoTs adaptability across diverse construction applications?*

- **Modular sensor integration framework for cross-platform adaptability:** Modular sensor integration framework for cross-platform adaptability: The deployment of SWIoTs in construction demands a modular approach to sensor integration that supports plug-and-play adaptability. Traditional IoT sensors often require custom configurations for each application, limiting their ability to function across multiple platforms [235,236]. A more scalable approach involves modular SWIoTs designs that incorporate standardized communication interfaces, such as open-source protocols such as Message Queuing Telemetry Transport (MQTT), Open Platform Communications (OPC), and interoperable hardware interfaces (e.g., USB-C, BLE, Zigbee). These standardized interfaces enable seamless integration with SHM platforms by ensuring that data from various sensors can be uniformly processed and analyzed. Additionally, they facilitate connectivity with energy management systems by allowing real-time data exchange for optimizing energy consumption in construction sites. In digital twin models, such modularity ensures that real-world sensor data can be accurately mapped to virtual representations, enhancing predictive maintenance and decision-making. Furthermore, AI-driven network orchestration can dynamically adjust sensor communication pathways to optimize connectivity while maintaining energy efficiency. By introducing universal integration frameworks, SWIoTs can achieve greater adoption across construction sectors, enhancing interoperability without requiring extensive hardware modifications. Future research should focus on developing flexible integration protocols that support real-time sensor deployment across a broad spectrum of construction applications.

b. *How can adaptive networking solutions improve SWIoTs interoperability and enable seamless data exchange in heterogeneous construction environments?*

- **Interoperability across IoT architectures for seamless data exchange:** Ensuring that SWIoTs can communicate across different IoT architectures requires the implementation of standardized data protocols that facilitate seamless information exchange [237,238]. However, the absence of universal IoT communication standards presents a significant challenge for integrating SWIoTs with cloud-based analytics platforms, edge computing systems, and real-time construction monitoring tools [239,240]. Without a unified framework, data silos emerge, limiting interoperability and reducing the efficiency of cross-platform sensor deployments. To address this challenge, AI-enhanced software-defined networking (SDN) offers a dynamic solution by autonomously managing and configuring communication layers. Unlike traditional network architectures that rely on static configurations, SDN leverages AI-driven algorithms to optimize sensor-to-cloud interactions in real-time. By incorporating adaptive routing mechanisms, SWIoTs can dynamically adjust their data transmission strategies based on factors such as network congestion, available bandwidth, and computational resource distribution. For instance, during peak data traffic, AI-based SDN can prioritize critical sensor streams while rerouting non-essential data to less congested channels, ensuring low latency and high-reliability communication. Furthermore, AI-driven SDN enables predictive network management by analyzing historical data patterns to anticipate connectivity bottlenecks and preemptively reallocate network resources. This capability is particularly beneficial in large-scale construction sites, where fluctuating sensor loads and environmental conditions demand a flexible and responsive networking approach. Future research should focus on adaptive networking solutions to enhance SWIoTs interoperability in construction. In the medium term (4–6 years), efforts may focus on protocol design and pilot validation, while in the longer term (8–12 years), research could advance toward standardized frameworks and large-scale deployment across diverse construction projects. Optimizing real-time sensor communication through intelligent energy management and edge-assisted processing will ensure reliable, low-latency data exchange. These advancements will enable seamless integration with existing IoT infrastructures, improving efficiency and scalability. Nevertheless, achieving scalable and interoperable SWIoTs also faces barriers. From a technical perspective, the energy burden of maintaining real-time connectivity and unresolved data security issues remain major challenges. Economically, the high cost of retrofitting legacy systems, the investment required for cross-platform integration, and uncertainties regarding standardization

timelines may limit widespread adoption. Addressing these barriers would be critical to enable truly architecture-agnostic and scalable SWIoTs frameworks in construction.

5.4. Limitations and further research

Despite its contributions, this study has several limitations. First, this review relied exclusively on Scopus as the primary database for literature retrieval, which may have led to the omission of relevant studies indexed in other databases such as Web of Science or IEEE Xplore. Future studies should incorporate a broader range of databases to ensure a more comprehensive and representative synthesis of existing literature. Second, the proposed conceptual cycle frameworks were developed from the 28 CSFs identified through a systematic literature review, which strengthens their theoretical grounding but still lacks empirical validation. Future research should address this limitation by incorporating both quantitative measures (e.g., Analytical Hierarchy Process (AHP), or Structural Equation Modeling (SEM)) and qualitative perspectives (e.g., expert evaluations, case studies) to enhance perceived objectivity, validate interdependencies, and establish the practical applicability of these frameworks in real-world construction environments. Third, the study hypothesized the interdependencies of the CSFs based on the literature without validation through expert opinions. To strengthen the theoretical framework and provide deeper insights into the causal relationships among the CSFs, future research should employ expert-based validation techniques, such as the Delphi method or fuzzy logic analysis. By addressing these limitations, future studies can enhance the robustness of the findings, contributing to the effective implementation of SWIoTs in construction.

6. Conclusion

This paper identified the CSFs for implementing SWIoTs in construction, developed conceptual frameworks, and discussed potential applications, research gaps, and future research directions. To achieve this, a systematic literature review was conducted by following the PRISMA guidelines, thereby retrieving 339 journal articles from the Scopus database.

The results revealed key research trends: (1) a growing annual publication trend in recent years indicating the interest of the studied topic among researchers and practitioners; (2) *Nano Energy* was the leading journal source, followed by *Chemical Engineering Journal* and *ACS Nano*; (3) China and the United States were the most active research contributors, with significant contributions from South Korea, the UK, and Taiwan; (4) laboratory experiments were the predominant research method, followed by simulations, field experiments, and theoretical modeling. In addition, 28 CSFs were identified and categorized into five thematic research domains, including (1) sensor materials and user comfort, (2) sensor structural design and topology, (3) sensor performance and functionality, (4) system integration and application, and (5) energy harvesting and power consumption. This categorization transforms fragmented insights into a structured framework that enables systematic analysis and cross-study comparability. It would also provide practitioners with a practical roadmap to prioritize key factors, thereby supporting more effective adoption of SWIoTs in construction.

This study developed two conceptual loop frameworks, namely (1) classification-based loop conceptual framework and (2) CSF-based loop conceptual framework, to understand the interrelationships between the identified CSFs for implementing SWIoTs in construction. The classification-based loop conceptual framework illustrated how advancements in one thematic CSF domain enhance others, creating a reinforcing cycle of technological progress. The CSF-based loop conceptual framework further uncovered complex interdependencies among CSFs for SWIoTs, emphasizing the crucial role of AI-driven data processing, energy efficiency, and seamless system integration in facilitating the adoption of SWIoTs in high-risk construction environments. Moreover, this study highlighted the existing and potential applications of SWIoTs in the construction industry, including SHM, real-time worker safety and human-centric monitoring, and real-time machinery health monitoring. These applications demonstrate the capability of SWIoTs to enhance safety, efficiency, and predictive maintenance, paving the way for their large-scale implementation in construction projects.

To ensure the successful deployment of SWIoTs in construction, three key research gaps must be addressed. First, SWIoTs materials require improvements in biomechanical adaptability, environmental resilience, and self-healing capabilities. Existing materials often lack flexibility, leading to discomfort, reduced adhesion, and limited long-term usability in harsh construction environments. Additionally, extreme temperatures, wind exposure, and corrosive elements can degrade sensor performance, requiring advancements in durable and adaptive materials to maintain functionality in real-world conditions. Second, achieving mission-critical energy autonomy remains a challenge due to the limitations of current energy harvesting and storage technologies. While SWIoTs rely on piezoelectric, triboelectric, thermoelectric, and photovoltaic systems, inefficiencies in energy conversion and storage hinder their ability to sustain long-term, self-powered operations. Fluctuating environmental conditions at construction sites further complicate stable energy harvesting, necessitating the development of integrated, high-efficiency energy systems to ensure uninterrupted performance. Third, system interoperability and scalability present major barriers to large-scale SWIoTs adoption. Existing frameworks often lack modularity and cross-platform compatibility, making integration with diverse construction applications difficult. The absence of standardized communication protocols limits seamless data exchange between SWIoTs, digital twin models, and building energy management systems, reducing their effectiveness in predictive maintenance and real-time monitoring.

Future research should focus on multi-material 3D printing and computational modeling to develop ergonomically optimized SWIoTs that enhance wearability, comfort, and data reliability. Parametric modeling can enable real-time design adjustments based on biomechanics and motion patterns, ensuring seamless integration into PPE and construction workflows. To improve durability in extreme environments, studies should explore nanocomposite-based substrates, thermal barrier coatings, and biomimetic aerodynamic designs to enhance heat resistance, wind stability, and vibration damping. Additionally, self-healing polymer coatings and hydrophobic nanofilms can strengthen corrosion resistance, extending sensor lifespan in harsh conditions.

For mission-critical energy autonomy, future research should integrate hybrid energy harvesting technologies, such as photovoltaics, thermoelectric generators, PENGs, and TENGs, to enable continuous, self-powered operation in smart buildings and construction sites. AI-driven energy management systems should optimize power distribution and real-time efficiency in high-demand environments. To ensure scalability and interoperability, future studies should develop modular sensor integration frameworks and implement standardized communication protocols such as MQTT and OPC. AI-driven network orchestration can enhance low-latency, high-reliability data exchange, supporting real-time monitoring and predictive maintenance. These advancements would drive efficiency, resilience, and large-scale adoption of SWIoTs in construction safety, structural health monitoring, and energy management.

6.1. Contributions to this study

This study advances the theoretical understanding of SWIoTs in construction by systematically identifying CSFs and their interdependencies. The development of the classification-based loop conceptual framework and the CSF-based loop conceptual framework would provide novel frameworks for analyzing the reinforcing relationships among sensor materials, structural design, performance, system integration, and energy efficiency. These frameworks would contribute to the existing literature by explaining how advancements in

one CSF domain drive improvements in others, offering a holistic approach to SWIoTs adoption. Furthermore, the study would bridge the gap between theoretical modeling and practical application by integrating insights from energy harvesting mechanisms, AI-driven analytics, and adaptive sensor materials.

The findings could offer practical guidance for industry professionals, technology developers, and construction managers aiming to effectively implement SWIoTs. The identified CSFs could provide a structured framework for designing robust, scalable, and high-performance wearable sensor systems that address industry challenges such as harsh environmental conditions, power limitations, and data security risks. These challenges are particularly relevant in SHM, real-time worker safety, human-centric monitoring, and machinery health monitoring, where SWIoTs enhance predictive capabilities and operational efficiency. For instance, SHM applications benefit from autonomous sensing accuracy certification and real-time signal transmission, enabling continuous tracking of structural integrity and early fault detection. In worker safety and human-centric monitoring, biocompatible and ergonomic SWIoTs improve long-term wearability, while AI-driven analytics refine stress and fatigue assessments, reducing injury risks. Similarly, machinery health monitoring leverages broad-spectrum sensing and embedded AI analytics frameworks, optimizing maintenance schedules and minimizing equipment downtime. To maximize these benefits, managers should focus on real-time energy management, seamless sensor integration, and automated data-driven decision-making, ensuring uninterrupted monitoring in high-risk construction environments. Additionally, adopting flexible self-powered generators and autonomous multi-source energy harvesting can enhance device longevity, reducing reliance on external power sources. Establishing standardized best practices tailored to construction settings will further bridge the gap between theoretical advancements and real-world applications, driving the large-scale adoption of SWIoTs in the industry.

From a policy perspective, this study underscores the need for regulatory frameworks that support the large-scale implementation of SWIoTs in construction by addressing key challenges in material optimization, energy harvesting, and system interoperability. The findings highlight the need for architecture-agnostic expansion to enable scalable and interoperable SWIoTs, emphasizing the importance of standardized communication protocols and interoperability guidelines. Policymakers should establish regulations that facilitate seamless integration across construction environments, ensuring compatibility between different sensor networks and digital platforms. Additionally, mission-critical energy harvesting for resilient building energy systems remains a key challenge, necessitating targeted policies that encourage advancements in biomechanical energy harvesting, adaptive energy storage, and wireless power transfer mechanisms.

CRediT authorship contribution statement

Yuxiang Huang: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Maxwell Fordjour Antwi-Afari:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Bochao Sun:** Writing – review & editing, Visualization, Investigation. **Jie Liu:** Writing – review & editing, Visualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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