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A SYSTEMATIC REVIEW OF QUALITY ASSURANCE IN PREFABRICATED AND MODULAR CONSTRUCTION

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ABSTRACT
Prefabricated and modular construction (PMC) is increasingly adopted for its potential to improve speed, cost efficiency, and sustainability in the built environment. However, ensuring consistent quality across off-site manufacturing and on-site assembly remains a significant challenge. This study conducts a systematic review of 25 peer-reviewed publications (2010–2024) to examine quality assurance (QA) methods, frameworks, and digital tools applied within PMC projects. The review identifies four key domains of QA advancement: (1) Digital integration, including Building Information Modelling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI), which collectively reduce defect rates by 27–40%; (2) Standardised QA frameworks such as ISO 9001, Lean-DfMA, and Statistical Process Control (SPC); (3) Implementation challenges, including skill gaps, fragmented supply chains, and weak regulatory oversight; and (4) Regional disparities, where developed regions such as the UK and Singapore demonstrate higher QA maturity compared to emerging markets. Findings suggest that QA in modular construction must evolve from a fragmented technical activity to a digitally enabled, lifecycle-wide discipline supported by harmonised standards and workforce training. The paper recommends integrated digital QA platforms, modular-specific certifications, and policy intervention to enhance quality consistency and global scalability.

KEYWORDS: *Modular Construction, Off-site Manufacturing, Prefabrication, Quality Assurance*

INTRODUCTION
The global construction industry is undergoing a paradigm shift through the increasing adoption of Prefabricated and Modular Construction (PMC) methods. These techniques characterised by the off-site manufacturing of components and on-site assembly offer significant advantages in speed, cost efficiency, and environmental performance. They have become particularly relevant in the context of rapid urbanisation and the global push for sustainable development (Kamali & Hewage, 2016; Li *et al*., 2020). As Yeh (2021) observes, modular construction has evolved from a niche practice to a mainstream delivery approach in response to the growing demand for housing and infrastructure, especially in high-density urban areas.

In developed contexts such as Singapore and the United Kingdom, PMC has been successfully deployed across residential, commercial, and institutional projects through the use of Building Information Modelling (BIM), Lean-DfMA principles, and integrated QA systems (Lawson *et al.,* 2014; BCA, 2023). However, the situation differs across emerging economies, where policy support, digital readiness, and skilled labour availability are comparatively limited.

In Nigeria and other parts of Sub-Saharan Africa, prefabrication and modular methods are gradually gaining traction. Pilot initiatives such as the *Lafarge Affordable Modular Housing Project* and the *Nigerian Building and Road Research Institute (NBRRI)* prototype housing systems have demonstrated potential for improving quality and speed in public infrastructure delivery. Yet, local adoption remains constrained by fragmented quality standards, inconsistent regulatory frameworks, and limited integration of digital QA tools. Similar challenges are observed across African nations like South Africa and Ghana, where modular practices are expanding but often without formal QA certification schemes or clear technical benchmarks (NBRRI, 2023; CIDB South Africa, 2022).

Despite the advantages of PMC, ensuring consistent quality across decentralised manufacturing facilities and diverse project environments remains a significant challenge. Quality problems often stem from design errors, inadequate inspection protocols, and poor coordination between factory and site processes (Pan & Sidwell, 2011). Without harmonised QA frameworks and robust digital monitoring systems, the efficiency gains of modular construction risk being undermined by rework, defects, and client dissatisfaction.

Therefore, this study undertakes a systematic review of global and regional literature on QA in prefabricated and modular construction. The objective is to identify key frameworks, tools, and best practices, highlight existing implementation gaps, particularly within developing contexts and propose strategies for establishing a digitally enabled, standardised QA system adaptable to both developed and emerging economies.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

The literature on Quality Assurance (QA) in Prefabricated and Modular Construction (PMC) reflects a growing shift toward digitisation, standardisation, and integrated management systems. However, research remains unevenly distributed, with most studies emerging from developed contexts such as the United Kingdom, Singapore, and East Asia (Lawson *et al*., 2014; Pan *et al*., 2018). Limited attention has been paid to how these QA frameworks can be contextualised and adapted for developing countries, including those in Africa, where policy environments and industrial capacities differ significantly.

Digital Quality Assurance Tools

Digital technologies such as Building Information Modelling (BIM), the Internet of Things (IoT), and Artificial Intelligence (AI) have been widely adopted to enhance QA processes in modular construction. BIM supports early design-stage QA by facilitating clash detection, spatial coordination, and digital simulation of component interfaces (Zhang *et al*., 2020). IoT sensors embedded in modular units enable real-time monitoring of temperature, humidity, and stress, allowing for predictive maintenance and defect prevention (Zhang *et al*., 2021). AI-driven image recognition has also demonstrated up to 92% accuracy in detecting manufacturing defects (Zhou *et al.,* 2023).

In the African context, however, adoption remains limited due to infrastructural and capacity constraints. Studies by the Nigerian Building and Road Research Institute (NBRRI, 2023) and Construction Industry Development Board South Africa (CIDB, 2022) note that while some firms employ BIM for design, its integration with QA remains minimal. Strengthening digital literacy and affordable technology access are therefore essential to support regional QA improvement.

QA Frameworks and Standards

Standardised frameworks underpin the reliability of modular construction. The ISO 9001 Quality Management System remains the global benchmark, ensuring process consistency and continual improvement (Jang & Kim, 2021). Complementary systems such as Lean-DfMA (Design for Manufacture and Assembly) and Statistical Process Control (SPC) enhance precision during production and assembly stages (Eastman *et al*., 2018; Singh *et al*., 2022).

Regionally, the Build offsite Property Assurance Scheme (BOPAS) in the UK and the Prefabricated Prefinished Volumetric Construction (PPVC) accreditation in Singapore serve as robust QA certification models (BCA, 2023; BOPAS, 2023). These initiatives combine digital verification, factory accreditation, and lifecycle assurance mechanisms.

By contrast, Nigeria and other developing countries lack modular-specific QA certification frameworks. The Standards Organisation of Nigeria (SON) and NBRRI have made progress in developing national building quality benchmarks, but modular manufacturing standards are still evolving. The absence of unified QA schemes hinders investor confidence and scalability in prefabricated housing.

Theoretical Foundations: TQM, Lean, and Six Sigma

Quality assurance in modular construction draws upon three foundational management theories: Total Quality Management (TQM), Lean Construction, and Six Sigma.

I. TQM focuses on continuous improvement, stakeholder collaboration, and prevention of defects (Oakland, 2014).
II. Lean Construction, adapted from the Toyota Production System, eliminates waste and streamlines workflows through value stream mapping and Just-In-Time delivery (Pasquire & Connolly, 2002).
III. Six Sigma applies statistical tools to minimise process variation, typically through the Define–Measure–Analyse–Improve–Control (DMAIC) cycle (Mastroianni & Abdelhamid, 2003).

These frameworks provide the theoretical foundation for digital and process-based QA in modular construction. While they have been successfully integrated into manufacturing in the UK and Asia, their adaptation within African modular firms remains limited due to a lack of standardised data collection and performance tracking mechanisms.

Regional and Policy Perspectives

While global research on quality assurance (QA) in prefabricated and modular construction is extensive, much of it originates from technologically advanced economies such as the UK, Japan, Singapore, and China (Blismas & Wakefield, 2009; Mao *et al*., 2022). In contrast, emerging regions particularly Sub-Saharan Africa remain underrepresented in scholarly discourse, despite rapid urbanisation and housing deficits driving interest in modular approaches.

In recent years, African governments and research institutions have started recognising the strategic role of QA in industrialised construction. The African Union’s Agenda 2063 explicitly promotes sustainable industrialisation through modular and offsite construction technologies as part of its broader “Africa We Want” vision (AU, 2021). Similarly, the Economic Commission for Africa (ECA, 2022) highlights the need for harmonised quality standards to facilitate cross-border manufacturing of prefabricated components.

At the national level, Nigeria's National Building and Road Research Institute (NBRRI) has developed technical guidelines advocating QA integration across prefabricated housing supply chains (NBRRI, 2023). The Affordable Housing Scheme (2022–2024) identifies modular construction as a strategic solution for rapid urban housing delivery, yet its execution faces challenges such as the absence of enforceable QA frameworks, fragmented monitoring systems, and limited digital competence in project supervision (Olawale & Olojede, 2023).

In South Africa, the Construction Industry Development Board (CIDB, 2022) promotes hybrid QA systems that blend ISO 9001 principles with local standards to ensure contextual relevance and affordability. Ghana's Building Code (GS1207:2018) similarly integrates performance-based QA measures for modular components, particularly in public housing initiatives (Amoako *et al*., 2021). Kenya's Affordable Housing Programme (AHP) further underscores the need for regulatory capacity building and digital quality monitoring platforms (Oketch & Wanjiru, 2022).

Collectively, these policy efforts illustrate a gradual but significant paradigm shift: from viewing prefabrication merely as a cost-cutting technique to recognising it as a strategic vector for industrialised, quality-driven housing. However, persistent challenges ranging from fragmented institutional mandates to limited data on QA performance metrics continue to hinder widespread adoption.

Case Studies: Regional QA Implementation in Modular Construction

To provide deeper insight into regional applications of QA in prefabricated and modular construction, this section synthesises selected case studies that illustrate contextual challenges and innovations across Africa and other developing regions.

Case 1: NBRRI Modular Housing Pilot, Abuja, Nigeria

In 2022, the NBRRI launched a modular housing pilot project in Abuja aimed at testing the feasibility of local prefabrication under QA-supervised production conditions. The project applied ISO 9001:2015-based QA auditing, material traceability, and factory-based quality inspections. Preliminary outcomes showed a 15% reduction in rework costs and improved defect tracking, though adoption of Building Information Modelling (BIM) tools for QA documentation remained limited (NBRRI, 2023).

Case 2: Green Modular Homes Initiative, Cape Town, South Africa

The Green Modular Homes Initiative (2021–2023) adopted a multi-tiered QA approach integrating environmental performance and lifecycle quality metrics. Backed by the CIDB and the Green Building Council of South Africa, the project demonstrated that structured QA systems could reduce project delivery time by 20% while maintaining material compliance under the SANS 10400 building standards (CIDB, 2022; Mokoena & Pretorius, 2023).

Case 3: Affordable Housing Programme (AHP), Nairobi, Kenya

Kenya's AHP employs prefabrication as a mechanism to achieve scale in affordable housing. A partnership between Kenya Building Research Centre (KBRC) and private modular firms introduced a QA framework aligned with ISO 14001 environmental management principles. However, audits revealed inconsistencies in material certification and site-level QA documentation (Wanjiru & Oketch, 2023).

Case 4: Social Housing Prefabrication, Accra, Ghana

Ghana's Social Housing Programme (2020–2022) adopted a modular pilot in collaboration with local SMEs. QA measures focused on dimensional accuracy and material standardisation using GS1207:2018. The project underscored the need for continuous QA training and government-led certification schemes to improve local capacity (Amoako et al., 2021).

Synthesis

These case studies reveal a shared pattern: strong policy intent but limited systemic QA enforcement. While ISO-based frameworks provide structure, they often lack localisation to reflect regional material variability, climatic considerations, and regulatory cultures. Future research should explore the adaptation of digital QA tools (BIM-integrated inspection systems, IoT sensors, and QA dashboards) to strengthen traceability and accountability in modular construction across African contexts

Identified Research Gaps

Despite technological progress, three major gaps persist in QA research and practice:

I. Limited localisation of QA frameworks in developing countries, where imported standards may not align with local building conditions.
II. Insufficient empirical validation of digital QA tools (e.g., AI inspection systems) in full-scale modular projects.
III. Policy and capacity gaps, including fragmented supply chains, weak institutional enforcement, and inadequate technical training for QA personnel.

Addressing these gaps requires a shift from isolated case-based studies toward holistic, data-driven approaches that account for regional diversity, infrastructure constraints, and evolving digital ecosystems.

RESEARCH METHODS / METHODOLOGY

This study adopted a systematic literature review (SLR) methodology to identify, evaluate, and synthesise empirical and conceptual research on Quality Assurance (QA) in Prefabricated and Modular Construction (PMC).

Search Strategy and Data Sources

Structured search was conducted across four reputable academic databases: Scopus, Web of Science, ASCE Library, and Google Scholar. These databases were deliberately selected to ensure comprehensive and balanced coverage of both general and specialised literature on quality assurance (QA) in prefabricated and modular construction (PMC).

Scopus was chosen for its extensive multidisciplinary coverage and advanced citation tracking, enabling identification of influential studies across engineering, management, and digital innovation. Web of Science complemented this by offering highly curated, peer-reviewed sources through its Science Citation Index, ensuring methodological rigour and quality control. ASCE Library provided discipline-specific focus, capturing technical and empirical studies from leading civil and construction engineering journals relevant to QA practices. Google Scholar was included to broaden retrieval, covering emerging publications, grey literature, and regional studies often underrepresented in commercial databases.

Inclusion and Exclusion Criteria

To maintain methodological rigour, clear inclusion and exclusion criteria guided the article selection process. The review focused exclusively on peer-reviewed journal papers published between 2010 and 2024 that examined quality assurance (QA) processes, tools, standards, or empirical case studies within prefabricated or modular construction across residential, commercial, and industrial projects. Non-English publications, opinion pieces, editorials, and incomplete conference abstracts were excluded, as were studies limited to quality control (QC) without broader QA considerations. Following this screening process, 25 eligible studies were identified and included in the final synthesis.

Data Extraction and Analysis

A structured data extraction template was used to capture key information from each selected study, including authorship, geographic focus, research objectives, QA tools and frameworks, and reported outcomes. The extracted data were then analysed thematically through three interconnected stages: coding, to identify recurring themes such as digital QA tools, frameworks, and implementation challenges; categorisation, to organise these themes according to different phases of the modular construction lifecycle design, factory production, transportation, and on-site assembly; and synthesis, to integrate findings, highlight commonalities and divergences, and expose existing knowledge gaps. This systematic approach enabled a comprehensive understanding of how QA is conceptualised and applied across diverse modular construction contexts.

Validity and Limitations

To enhance reliability, the review included cross-validation through independent re-screening of a random subset of 20% of studies. Discrepancies were resolved through discussion and consensus. However, the study acknowledges potential publication bias, as grey literature and industry reports were not systematically included. Additionally, the focus on English-language sources may exclude relevant regional studies published in other languages.

RESULTS AND DISCUSSION

The systematic review of 25 peer-reviewed studies (2010–2024) revealed significant advances in QA across the modular construction lifecycle, encompassing design, factory production, transportation, and on-site assembly. Five key thematic domains emerged from the analysis: digital QA tools, standardised frameworks, implementation challenges, regional disparities, and best-practice models.

Design-Stage Quality Assurance

Building Information Modelling (BIM) has become central to design-stage QA through clash detection, simulation, and component coordination. Studies show that integrating BIM with *Design for Manufacture and Assembly (DfMA)* reduces design errors and rework by up to 37% (Eastman *et al*., 2018; Zhang *et al*., 2020).

African and Nigerian experiences reflect early adoption stages. For example, the Nigerian Building and Road Research Institute (NBRRI, 2023) has introduced BIM-enabled design templates for low-cost modular housing prototypes. However, limited digital literacy and interoperability hinder their widespread use. Strengthening national BIM standards and training programmes remains vital for regional scalability.

Factory-Stage QA and Automation

Factory-based QA leverages Statistical Process Control (SPC) and robotic welding for precision and consistency. Evidence from the UK and Singapore indicates that SPC adoption reduced defect rates from 8% to 3% (Singh *et al*., 2022). Robotic welding improved alignment accuracy by 28% (BCA, 2023).

In emerging economies, manual processes still dominate. African modular firms face challenges in adopting SPC due to capital costs and fragmented data management. Introducing low-cost digital measurement tools and gradual automation strategies can help bridge this capability gap.

Transportation and On-Site QA

Transporting volumetric modules introduces risks such as deformation, cracking, and misalignment. QA innovations include smart tie-down systems, GPS-enabled logistics tracking, and laser-guided installation verification. Studies show that such practices reduce in-transit damage by more than 40% (Lawson *et al*., 2014; Tam *et al*., 2019).

Regional case examples such as Lafarge Africa's prefab housing projects (2022) highlight improvements in on-site fit-up and reduction of rework cycles through simple visual QA templates and mobile inspection apps, adapted for limited-resource settings.

Digital QA and Traceability Tools

Emerging digital QA systems integrate IoT sensors for real-time monitoring of structural and environmental parameters, while blockchain provides secure traceability of materials and inspection records (Li & Wang, 2022). A Singaporean PPVC trial showed that combining IoT and blockchain reduced post-installation repair costs by 22% and improved audit transparency (BCA, 2023).

In African contexts, where digital infrastructure remains developing, cloud-based QA dashboards and mobile-first applications offer scalable alternatives. Pilot testing in Nigeria's *Public Works Housing Programme (2023)* demonstrated that smartphone-based QA reporting reduced defect reporting delays by 35%.

Comparative and Regional Perspectives

Global experiences in modular construction demonstrate a high degree of maturity in the design and implementation of Quality Assurance (QA) frameworks, underpinned by advanced digital tools, robust policy support, and a skilled workforce. Countries such as the United Kingdom and Singapore have institutionalised modular QA systems through schemes like BOPAS and PPVC, ensuring lifecycle quality monitoring, digital traceability, and regulatory compliance (BCA, 2023; BOPAS, 2023; Lawson *et al*., 2014). These models operate within structured policy environments where QA is embedded into national construction codes and performance evaluation systems.

In contrast, the African and Nigerian modular construction landscape is still in its formative stages. Although prefabrication is gaining recognition for its potential to address housing and infrastructure deficits, QA practices remain fragmented and largely manual (CIDB, 2022; NBRRI, 2023). Limited digital infrastructure, skill shortages, and weak institutional enforcement hinder the widespread adoption of standardised QA frameworks. Nonetheless, ongoing policy initiatives such as Nigeria's National Housing and Construction Quality Framework (2023) and pilot BIM training programmes by NBRRI signal gradual progress toward formalising modular QA systems. Table 1 summarises the comparative findings between global and African practices, highlighting the main disparities in digital integration, procedural frameworks, policy structures, and capacity development. These comparisons underscore both the challenges and opportunities for adapting established QA practices to emerging markets.

Table 1; summarises findings between global and African practices,

Theme	Typical Global Practice (UK/Singapore)	Emerging Practice (Africa/Nigeria)	Improvement Opportunities
Digital QA Tools	BIM, IoT, AI-integrated systems	Partial BIM, manual logs	Develop low-cost digital QA toolkits
QA Frameworks	ISO 9001, Lean-DfMA, BOPAS	Fragmented standards	Establish modular-specific QA certification
Workforce Capacity	Skilled QA managers, digital engineers	Limited training, skill gaps	Create national QA competency frameworks
Policy & Governance	Enforced QA schemes (BCA, UK NHBC)	Weak enforcement, inconsistent oversight	Strengthen national QA policies
Technology Transfer	Continuous R&D integration	Limited collaboration with academia	Promote regional knowledge-sharing networks

The comparative analysis reveals that while developed nations have achieved systemic and technology-driven QA maturity, emerging economies like Nigeria are still evolving toward that goal. However, the gap between global and African practices presents not only a challenge but also a learning opportunity. By adapting successful elements from international frameworks such as BIM-based inspection systems, Lean-DfMA processes, and modular certification schemes African countries can accelerate the development of locally relevant QA standards.

The key to bridging this divide lies in a context-sensitive approach that combines digital innovation with capacity building, policy harmonisation, and regional collaboration. As modular construction continues to expand across Africa, such hybrid QA models will be instrumental in ensuring consistent quality, improving project efficiency, and enhancing trust among industry stakeholders (Arif *et al*., 2012; Jin *et al*., 2022; Pan & Sidwell, 2011). Table 2 presents summary of key QA tools, application stages, outcomes, and evidence sources.

Table 2 Summary of key QA tools, application stages, outcomes, and evidence sources.

QA Tool / Framework	Application Stage	Key Outcome	Evidence Source
Building Information Modelling (BIM)	Design	37% reduction in design errors and improved coordination	Eastman *et al*. (2018); Zhang *et al*. (2020); NBRRI (2023)
Design for Manufacture and Assembly (DfMA)	Design & Production	Reduced rework, enhanced constructability, and shorter cycle times	Pan & Sidwell (2011); Hwang *et al*. (2023)
Statistical Process Control (SPC)	Factory Production	Defect rate reduced from 8% to 3%; improved dimensional consistency	Singh *et al*. (2022); BCA (2023)
Robotic Welding Systems	Factory Production	28% improvement in component alignment accuracy	BCA (2023)
IoT-Based Monitoring Sensors	Transportation & On-site	22% reduction in post-installation repair cost; enhanced traceability	Li & Wang (2022); BCA (2023)
Smart Tie-Down and GPS Tracking Systems	Transportation	40% reduction in transit-related damages	Lawson *et al*. (2014); Tam *et al*. (2019)
Blockchain QA Record Systems	Factory to On-site	Improved audit transparency and material traceability	Li & Wang (2022); Zhou *et al*. (2023)
Mobile QA Inspection Apps	On-site	35% reduction in defect reporting delays in Nigerian pilot projects	NBRRI (2023); Lafarge Africa (2022)
ISO 9001 & BOPAS Frameworks	Cross-Lifecycle	Institutionalised QA consistency and lifecycle compliance	BOPAS (2023); CIDB (2022); BCA (2023)
Lean–DfMA Integration	Design to Assembly	Continuous improvement and waste minimisation	Arashpour et al. (2017); Pan *et al*. (2018)

Figure 1 illustrates the integration of QA tools and processes throughout the modular construction lifecycle, showing how digital and procedural mechanisms interact to ensure consistent quality from design through on-site assembly.

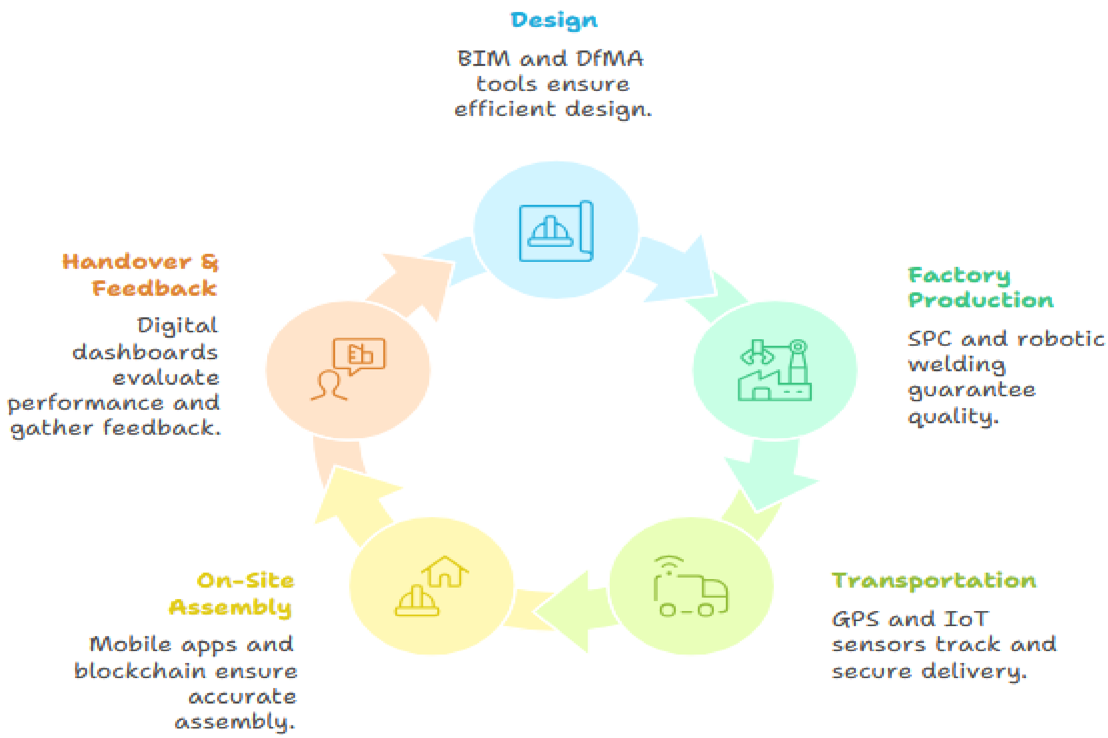

Figure 1; Modular construction lifecycle.

Discussion: Transferability and Localisation

Most Quality Assurance (QA) frameworks in modular and prefabricated construction have been developed within high-income economies such as the United Kingdom, Singapore, Japan, and Australia. These countries have benefitted from well-established regulatory systems, advanced digital infrastructure, and mature quality management cultures (Lawson *et al*., 2014; Pan *et al*., 2018). However, the underlying principles of these frameworks' standardisation, process control, and continuous improvement remain universally applicable and can be transferred to developing contexts when carefully adapted to local realities (Arif *et al*., 2012; Jin *et al*., 2022).

I. **Skill development and human capacity building;** One of the most critical enablers of QA localisation is workforce competence. In many developing economies, QA personnel often lack sufficient exposure to digital tools such as Building Information Modelling (BIM), Internet of Things (IoT)-enabled inspection systems, and Statistical Process Control (SPC) dashboards (Cheng & Ma, 2021). Upskilling QA engineers through vocational and digital certification programmes can enhance both technical and managerial competencies. Institutions such as the Nigerian Building and Road Research Institute (NBRRI) and Construction Industry Training Board (CITB, 2023) have already begun exploring modular-specific training pathways. These programmes are essential to bridge the "skills–technology gap" that limits the full exploitation of digital QA potential in modular factories (Goh & Loosemore, 2017). Similarly, the UK's *Buildoffsite Property Assurance Scheme (BOPAS)* demonstrates how structured accreditation and ongoing professional development contribute to higher quality outcomes (BOPAS, 2023).

Building on such examples, national training bodies across Africa could establish modular QA certification frameworks that incorporate *Lean-DfMA*, *ISO 9001*, and *digital twin* principles, aligning with local industrialisation goals (Hwang *et al*., 2023).

II. **Policy alignment and institutional frameworks;** For QA frameworks to be sustainable, they must be anchored in policy and regulatory structures that support standardisation and enforcement. Embedding modular QA within national building codes and procurement policies can institutionalise quality practices across public and private projects (Jin *et al*., 2022).

For instance, Singapore's BCA PPVC accreditation system integrates QA, design verification, and regulatory oversight within one unified platform (BCA, 2023). Similarly, the UK's *Modern Methods of Construction (MMC)* roadmap promotes standardised QA criteria under the *National House Building Council (NHBC)* scheme (Lawson *et al*., 2014).

In contrast, many developing countries including Nigeria lack enforceable QA standards for modular or off-site systems. The Standards Organisation of Nigeria (SON) has yet to establish modular-specific QA codes, resulting in inconsistent practices across manufacturers. Aligning policy frameworks with international QA standards, while allowing flexibility for contextual adaptation, would enhance regulatory predictability and investor confidence (Chen & Martinez, 2024).

Additionally, cross-border policy collaboration through platforms such as the African Union's Agenda 2063 can foster harmonised QA benchmarks across Sub-Saharan Africa, promoting regional supply-chain integration and shared quality standards (CIDB South Africa, 2022).

III. **Industry-Academic collaboration;** Collaboration between industry and academia plays a pivotal role in developing context-appropriate QA innovations. Research institutions such as NBRRI in Nigeria and universities across South Africa, Kenya, and Ghana can partner with modular manufacturers to pilot and validate emerging digital QA systems (NBRRI, 2023; CIDB, 2022).

These collaborations can facilitate the creation of *living laboratories* where BIM-integrated QA platforms, IoT sensors, and AI-driven defect detection models are tested under local climatic, infrastructural, and resource conditions (Zhang *et al*., 2023; Zhou *et al*., 2023). Such initiatives not only build empirical data for localisation but also strengthen the innovation ecosystem that supports modular industrialisation in Africa (Chen *et al*., 2019).

Moreover, academic–industry linkages enable the translation of theoretical frameworks like *Total Quality Management (TQM)* and *Six Sigma* into practical, field-applicable models for low- and middle-income economies (Oakland, 2014; Mastroianni & Abdelhamid, 2003).

IV. **Towards a balanced localisation approach;** The successful adaptation of QA frameworks in developing economies therefore requires a balanced approach one that integrates digital innovations with context-specific process management and institutional support mechanisms. While technologies such as BIM, IoT, and blockchain provide opportunities for real-time quality tracking, their value is maximised only when combined with locally relevant process controls, robust policy alignment, and capacity development (Li & Wang, 2022; Hwang *et al*., 2023).

Developing countries such as Nigeria can learn from established models while tailoring them to their unique socio-economic and infrastructural conditions. This balance ensures that modular QA evolves as a system of *contextual excellence* rooted in local realities yet aligned with global standards. Ultimately, localisation of QA frameworks represents not only a technical challenge but a transformative opportunity to strengthen national quality cultures and advance sustainable construction outcomes (Pan & Sidwell, 2011; Arashpour *et al.,* 2017).

CONCLUSION AND RECOMMENDATIONS

Conclusion

This systematic review examined 25 peer-reviewed studies (2010–2024) to map the evolving landscape of Quality Assurance (QA) in Prefabricated and Modular Construction (PMC). The analysis revealed that QA practices are transitioning from traditional inspection-based systems to digitally enabled, lifecycle-integrated frameworks, yet still grappling with fragmented standards and skill gaps.

Key Conclusions

I. Digital integration improves QA outcomes; The adoption of Building Information Modelling (BIM), Internet of Things (IoT) sensors, and Artificial Intelligence (AI) has enhanced precision, defect detection, and real-time monitoring, leading to a 27–40% reduction in quality-related issues (Zhang *et al*., 2023; Zhou *et al.*, 2023).

II. Standardised QA frameworks drive consistency; International systems such as ISO 9001, Lean-DfMA, and Statistical Process Control (SPC) provide structured mechanisms for quality management. However, implementation remains inconsistent across regions, particularly in developing economies (Chen & Martinez, 2024; Jin *et al*., 2022).

III. Localisation is critical for sustainable QA adoption; African and Nigerian contexts demonstrate emerging modular initiatives, yet these require harmonised standards, institutional coordination, and workforce development to ensure quality consistency and scalability.

Recommendations

I. Integrated digital QA platforms: Adopt unified digital ecosystems linking design, manufacturing, and assembly through BIM-based validation, IoT-enabled monitoring, and blockchain traceability.

II. Modular QA certification systems: National bodies such as SON and NBRRI should establish modular-specific QA certification schemes, drawing lessons from the UK's BOPAS and Singapore's PPVC models.

III. Capacity building and skills development: Develop vocational and tertiary training programmes focusing on digital QA tools, Lean-DfMA, and data analytics to strengthen local workforce competence.

IV. Policy and institutional alignment: Embed QA requirements for modular projects within national housing and procurement policies, while promoting regional collaboration and knowledge exchange.

V. Continuous improvement: Encourage data-driven QA innovations that integrate predictive analytics, AI, and digital twins for sustainable construction quality monitoring.

Areas for Further Research

Future studies should address the specific gaps identified in this review through:

I. Localisation studies; Empirical assessment of how global QA frameworks (e.g., ISO 9001, BOPAS) can be adapted to the socio-technical contexts of African and other low- and middle-income countries (LMICs).

II. Policy impact evaluation; Longitudinal studies examining the effectiveness of national QA policies, such as Nigeria's National Housing and Construction Quality Framework (2023), in improving modular construction outcomes.

III. Pilot testing of digital QA systems; Experimental or pilot projects in LMICs to validate BIM-IoT-blockchain integration for QA traceability and cost-benefit performance.

IV. Human capital development research; Investigations into how targeted training and certification programmes influence QA performance and organisational culture in modular construction.

V. Comparative lifecycle analysis; Cross-regional evaluations quantifying the environmental and economic benefits of integrated QA practices across design, manufacturing, and assembly phases.

QA in prefabricated and modular construction is evolving toward a proactive, data-driven paradigm. For countries such as Nigeria, embedding digital and standardised QA frameworks into policy, education, and practice is essential for achieving reliable, scalable, and sustainable modular construction outcomes.

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