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Assessing the sustainability benefits of modular construction for achieving sustainable development goals in housing delivery in Nigeria

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Abstract

The Nigerian construction industry is largely based on linear and unsustainable approaches, which have resulted in housing deficits, affordability problems and environmental degradation. Though MC contributes to global sustainability, there is limited empirical evidence from developing countries such as Nigeria and its association with SDGs. Underpinned by integrating the triple bottom line (TBL) theory and innovation diffusion theory (IDT), this study fills this gap by critically examining how the adoption of MC in housing production contributes to achieving SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production). The structured questionnaire was used to collect 124 data from construction experts using purposive and snowball sampling. With a reliability index of over 0.70, the gathered data was analysed using frequency, percentage, mean score, coefficient of variance (CV), Kruskal-Wallis's test, and Spearman correlation analysis. The study found that the environmental and social benefits of MC have a significant, positive impact on the SDGs 9, 11, and 12. The economic benefits exhibits no statistically significant relationship with SDG 9 and SDG 11 but has a weak statistically significant relationship with the attainment of SDG 12. The novelty of this research is the development and empirical validation of an integrated TBL-IDT framework that quantitatively correlates the environmental, economic and social benefits of MC to the achievement of SDGs 9, 11 and 12 in a developing context. The study advances knowledge on MC and proposes a decision-making framework for the delivering SDG-aligned sustainable housing.

Keywords Modular construction, Sustainable development goals (SDGs), Sustainability, Construction stakeholders, housing, construction industry, off-site construction



1 Introduction

The construction industry continues to adopt conventional, traditional construction systems that are detrimental to the environment in numerous ways. For instance, the industry is responsible for 37% and 50% of the global CO₂ emissions and material extractions from nature, respectively (UN Environment Programme [71]). The Construction sector's activities generate substantial quantities of waste and emission that negatively affect land, air, and water ecosystems. Furthermore, traditional systems consume significant quantity of materials, energy, and water, which can cause an imbalance in the ecosystem [5]. This pattern is evident in both mature nations such as the US and the EU, ([68]; Council of the European Union, [11]), Canada [27], Norway [30], and China [8], where the construction industry accounts for appreciable proportion of materials consumption, carbon emissions and national energy use. This situation is even more pronounced the building sector of Africa, especially in Nigeria where the traditional construction system is still in use [4, 53].

As a result of the unsustainable approach of the conventional construction system, a high volume of construction waste is produced. Construction and demolition activities are responsible for the largest percentage of solid waste in many countries (e.g., 60% and 50% in the USA and UK, respectively, and 37% in Hong Kong [19], and 38.4% in the EU (Eurostat, [14])). These have placed enormous pressure on waste management systems, leading to increased costs and challenges in effectively managing the growing volume of construction waste. These alarming statistics underscore the substantial impact of the construction industry on energy consumption, natural resource exploitation, carbon emissions, and waste generation. The consequences have led to a global call for a more sustainable, environmentally friendly production system to meet the housing needs of the rapidly growing global population. In response, off-site production systems have increasingly been recognised and advocated due to their potential to enhance construction projects' sustainability performance across the environmental, economic and social dimensions [32]. Modular construction (MC) is an off-site production system designed to enhance the viability and sustainability performance of the construction industry [27]. MC employs 3D modular modules that are sustainably built in a controlled environment off-site, transported to the construction site, and suitably installed in their proper locations within the structure [44]. MC is an eco-friendly approach that boosts productivity and labour efficiency, eliminates waste, and offers better quality and safety performance [38]. A fundamental requirement of Modern construction methods, such as MC, is to enhance sustainability by minimising the environmental, economic, and social impacts of the building and construction sector. These may have contributed enormously to the increased attention MC is receiving for housing production in recent times [36].

Lawson et al. [41] confirmed that MC is well established in Europe, as evidenced by its widespread use in high-rise building projects across the continent. MC is typical in the construction markets of mature countries, such as Germany, Japan, Sweden, the USA, and the UK, and is rapidly gaining traction in China and Australia [19]. With an estimated growth rate of 6.3%, the global modular construction market is predicted to reach approximately US\$215 billion by 2025 (PBC Today [60]). The UK modular building market share is expected to increase from US \$ 6.95 billion in 2023 to US\$ 9.38 billion by 2028. This represents a forecasted compound annual growth rate (CAGR) of 6.17% for the period 2023–2028 (Mordor Intelligence [42]). In the same vein, the Chinese MC

market is projected to reach US\$53.4 billion by 2030, with an 8.6% CAGR forecast, while Japan and Canada are expected to grow by 5.4% and 5.7%, respectively, and Germany's CAGR is projected to grow by 6%. By 2029, the MC market size in the Middle East and Africa is anticipated to be \$10.76 billion, with a CAGR of 7.9%, driven largely from the significant contributions from the United Arab Emirates and Saudi Arabia [13]. These trends indicate the growing role of MC in addressing housing production challenges while contributing to the achievement of the global sustainability goals.

While modular construction has been extensively researched in developed nations, its application and sustainability significance in developing countries have yet to be adequately explored. Existing studies in Nigeria [5, 40, 77] have examined MC with a focus on cost, efficiency, and housing delivery, but none have empirically assessed MC's sustainability impact in relation to the SDGs. This represents a significant gap, as SDGs 9, 11, and 12 can address innovation, urban sustainability, and responsible production, which are key challenges for the housing sector in Nigeria [5, 40]. In addition, most existing research is conceptual or descriptive, thus lacking robust statistical validation on how MC techniques contribute to sustainability in measurable terms. Moreover, Ginigaddara et al. [25] call for empirical studies linking MC adoption with some selected SDGs. Therefore, this study aimed to assess the relationship between the benefits of MC adoption and sustainability, with a focus on their contributions to SDGs 9, 11, and 12. Fei et al. [18] noted that 10 of the 17 SDGs are prevalent, with SDGs 9, 11, and 12 standing out among these 10 and ranking within the top five; hence, the rationale for their focus in this study. Although SDGs 6 (Clean Water and Sanitation) and 13 (Climate Action) were found to be important and highly prevalent in construction-based sustainability discourse [18], they were not considered in this study because their attainment is largely indirect and dependent on the operational phase of construction projects. SDGs 9, 11, and 12, which can be directly measured and are impacted by adopting MC at the project delivery phase, were therefore selected for this study. The drawback to implementing modern, innovative, and sustainable construction methods in the construction industry is partly due to the lack of awareness about the benefits of these methods among key sector actors.

Information on the sustainability benefits of MC is expected to positively influence industry stakeholders' decision to adopt MC in Nigeria and other developing countries in Africa and beyond. This study combined TBL and IDT within one framework to illustrate the sustainability implications of modular construction. It provides empirical evidence on the extent to which the sustainability benefits of MC contribute to achieving SDGs 9, 11 and 12 in a developing setting. The study also develops an SDG-driven decision-making framework that translates these empirical findings into practical guidance for policymakers and industry stakeholders.

1.1 Aim and objective of the study

Flowing from the research gaps, this study aims to examine the sustainability impacts of adopting MC for housing delivery and its relationship to selected SDGs in Nigeria.

The specific objectives of the study are;

1. Identify and assess the environmental, economic, and social sustainability benefits of adopting MC in housing production.

2. Examine construction professionals' perceptions of the contribution of MC to the attainment of SDGs 9, 11, and 12.
3. Assess the relationships between the sustainability benefits of MC and the selected SDGs.
4. Develop an SDG-driven decision-making framework to support MC adoption for sustainable housing delivery.

This study adopts an integrated framework of Innovation Diffusion Theory (IDT) and the Triple Bottom Line (TBL) to achieve the study's purpose.

1.2 Literature review

1.2.1 Conceptual clarification of construction approach

This study uses clear and consistent terminology to distinguish between related construction approaches. Off-site construction (OSC) is a construction process in which building components are manufactured wholly or partly in a factory environment and then transported to site for assembly [19, 25]. In OSC, prefabrication is defined as the off-site production of discrete building elements (e.g. panels, frames or sub-assemblies) and their assembly on-site [44].

The study focuses on modular construction (MC), which is a more advanced form of prefabrication. MC refers to the off-site production of volumetric three-dimensional modules that are fully or near-fully completed prior to transportation and installation [27, 36]. These modules incorporate structural, architectural and sometimes mechanical elements within a controlled factory environment. The final built assets that are produced using MC techniques are referred to as modular buildings (MB). For consistency purposes, this study refers to the innovation being studied as “modular construction” and only uses OSC and prefabrication where broader conceptual distinctions are necessary.

1.2.2 Housing shortage and MC

The housing crisis is a global phenomenon. For instance, in the UK, Parisi and Donyavi [58] confirmed that soaring property prices, a dormant supply, and a growing affordability problem exacerbate the housing crisis. The United States is 1.5 million homes short of meeting its housing demand (World Economic Forum [74]). Reports covering 2013 and 2019 indicate that cities such as Hong Kong, Sydney, and London have the worst affordability issues [22]. The cost of housing and its associated impact on affordability have more than doubled since the 2008 financial crisis, and this trend has worsened due to the COVID-19 pandemic. A study of 200 cities from various nations revealed that 90% of them are unaffordable to live in, as the average home cost exceeds three times the average household income (World Economic Forum [74]).

Furthermore, experts estimate that the housing and affordability crisis will impact over 1.6 billion people globally by 2025 (World Economic Forum, [74]). This crisis is worst in the rapidly urbanising regions of Africa and Asia-Pacific, where housing and infrastructure provision fail to keep pace with growing populations and cities (United Nations [70]). Urbanisation, population growth, and dynamics in the socio-economic conditions of the citizenry, as well as a persistent mismatch between housing demand and supply [58], are responsible for the housing shortage. In Nigeria, a country in Africa, the combined housing shortage in major cities is over 17 million [64], and with the pressure of

a yearly rural-urban migration rate of 5.5% [77], Nigeria will face an unbearable housing crisis if something drastic and innovative is not done.

To mitigate housing shortage and affordability issues, a recent report by the World Green Building Council [75] suggested that 2 billion homes need to be built over the next 75 years. That is, approximately 96,000 new affordable and sustainable houses must be built every day to address the global housing shortage. One of the sustainable ways to achieve an affordable, sustainable home is MC, which is posited to mitigate the housing shortage significantly by offering an efficient, faster, and lower-cost method of producing houses compared to the traditional approach [24].

MC techniques are poised to transform and scale up housing production to address the demand gap and improve the affordability of housing for the masses [58]. MC is suitable for low-cost, affordable housing construction in developing countries [43]. The numerous opportunities and advantages of MC in housing production led Ferdous et al., [19] to conclude that prefabricated construction is the next generation of housing. Nazir et al. [46] concluded that MC performances, in terms of cost, time, and quality, significantly outperform those of the traditional construction approach in housing production. It has been established that MC techniques foster sustainability by minimising resource consumption and waste generation during construction [35].

1.2.3 Modular construction in the nigerian context

The Nigerian construction sector has been plagued with persistent structural and operational challenges which still impact housing delivery. One of the most pressing issues is the housing deficit, which stands at more than 17 million units, fuelled by rapid urbanisation, population growth, and inadequate financing mechanisms [49, 64, 77]. The delivery of housing is limited by high construction costs, restricted access to mortgage finance, difficulties in land acquisition and infrastructural deficits, which together constrain the large-scale production of housing.

Despite the global progress in modern construction techniques, the Nigerian construction industry still relies heavily on conventional labour-intensive construction methods. The conventional methods are usually inefficient in terms of long project durations, high wastage of materials, poor quality control and environmental degradation [5, 40]. Such systems are predominant, in part due to institutional inertia, and limited exposure to alternative delivery models such as modular construction (MC).

High initial capital investment limited technical expertise and poor local manufacturing capacity for prefabricated components are among several barriers to MC adoption in Nigeria. Scalability is further constrained by the lack of established supply chains and industrialised production facilities. Furthermore, stakeholder resistance to change and concerns regarding cost implications and design flexibility continue to hinder adoption [3, 64].

The regulatory, policy and institutional environment for MC is still in its infancy. Lack of clear standards, guidelines and building codes for off-site and modular construction systems. This regulatory void creates uncertainty for developers and investors, which undermines confidence in MC as an alternative to conventional construction methods. Moreover, the shift to innovative construction methods is further hindered by insufficient government incentives and poor enforcement mechanisms [5, 6].

Another big hurdle is the local manufacturing capacity. Nigeria's industrial base for manufacturing the modular components is still developing, leading to dependence on foreign technologies and materials. This dependence adds to project costs and compromises the economic viability of MC adoption in large scale housing delivery. Therefore, to reduce costs and enhance the competitiveness of MC, strengthening domestic manufacturing capabilities is required [49].

Finally, the perception and awareness of MC among construction professionals are still uneven. Nevertheless, practical implementation remains low despite growing awareness of its efficiency and sustainability benefits. The gap arises from inadequate training, lack of demonstration projects, and poor dissemination of knowledge in the industry [5, 77]. Education, training and pilot projects are required to strengthen professional capacity to improve confidence in MC and speed up its uptake.

These contextual challenges, generally, underscore the importance of specific interventions to facilitate MC uptake in Nigeria. Institutional, technical and socio-economic barriers will need to be overcome in order to unlock the potential of modular construction as a sustainable solution for housing delivery and SDG achievement.

1.2.4 Sustainability benefits of modular construction methods

Modular construction (MC) has been increasingly promoted as a sustainable alternative to conventional construction methods due to its potential to improve environmental, economic and social outcomes. Previous studies generally support the idea that MC is beneficial for sustainability, but the magnitude and type of such benefits differ across countries, project types and industry context. However, the transfer of these benefits to developing countries is not guaranteed, as industrial capacity, regulatory frameworks, logistics infrastructure, and market maturity vary [27, 34, 41, 79]. For example, studies from the developed economies of the UK, Canada, Sweden, Australia and China often report improvements in productivity, waste reduction, quality control and construction speed [9, 55, 61].

There is a large degree of consensus in the literature that MC has environmental benefits. Several studies have demonstrated the advantages of factory-based production over traditional construction methods in terms of material waste reduction, resource efficiency, recycling opportunities, and minimal site disturbances [21, 34, 47]. Nahmens and Ikuma, [45] reported large reductions in construction waste, while Parisi and Donyavi [58] emphasised the high recyclability of modular building materials. Similarly, Chen et al. [10] and Yang et al. [79] stated that MC enhances energy efficiency and reduces environmental effects over the building lifecycle. Such results indicate a general agreement that MC facilitates responsible consumption and responsible production of resources. Some studies, however, caution that environmental benefits are not guaranteed. Transportation distances, energy consumed in manufacturing facilities and the embodied carbon of module production and delivery could affect the sustainability performance of MC. Thus, the net environmental advantage of MC depends on project-specific and contextual factors, in particular the energy mix of the factories and the energy efficiency of the transportation networks [27, 34].

There has also been extensive research into the economic benefits of CM, but the results are less consistent than those reported for environmental benefits. Common studies show that MC has the benefits of reducing construction time, enhancing

productivity, improving quality, and decreasing the amount of labour [38, 47, 72]. Lawson et al. [41] and Gallo et al. [21] also found that the shorter the project duration, the lower the preliminary costs, and the earlier the occupancy, the earlier the returns on investment. Munmulla et al. [43] also reported significant reductions in labour and total construction costs compared to conventional methods. But some studies say that scale, standardisation and market demand largely determine economic gains. The substantial capital required for building manufacturing facilities, purchasing specialised equipment, setting up supply chains, and training employees can overshadow the short-term financial gains, particularly in developing countries where the markets for MC are still in their infancy [31, 56]. Thus, although MC offers the potential for cost savings and productivity gains they are often reliant on the availability of adequate industrial capacity and a continuing project demand.

The social sustainability implications of MC are increasingly recognised by contemporary literature. It is generally agreed among studies that MC offers safer and healthier working environments as a large proportion of construction activities is shifted from uncontrolled site conditions to factory settings [36, 41, 79]. MC has also been associated with less community disruption, lower noise pollution, better access to housing, and greater resilience during disaster situations [10, 59]. Moreover, Jiang et al. [33] and Ziaesaedi and Noroozinejad [82] assert that modular housing can enhance social inclusion and community involvement through increased design flexibility and adaptability to local requirements. However some research have questioned if MC could reduce employment opportunities of traditional site-based workers because of increased automation and industrialisation. There could be new jobs in manufacturing and logistics, but the pattern of employment benefits might be different than with traditional construction methods. This indicates that the socio-economic implications of MC could involve both opportunities and trade-offs, contingent upon labour market conditions and the structure of the construction industry ([63]; Buildings and Cities, [7]).

Overall, the literature suggests that MC has great potential to contribute to sustainability by protecting the environment, being economically efficient and improving social aspects. However, the evidence also suggests that such benefits are not universally consistent across countries and project contexts. Their realisation is contingent upon several enabling conditions like supportive government policies, efficient transport infrastructure, availability of skilled labour, standardised designs, investment in manufacturing facilities and market acceptance of modular technologies [23]. Therefore, findings reported in developed countries cannot be directly generalised to developing economies like Nigeria. These contextual uncertainties highlight the need for empirical research on the extent to which the sustainability benefits of MC translate into quantifiable contributions to sustainable development goals in specific national contexts. Evidence of this is still scarce in developing countries, making it necessary to focus this study on the relationship between the sustainability benefits of MC and the achievement of SDGs 9, 11 and 12 in Nigeria.

A summary of the selected sustainability benefits of modular construction is presented in Table 1. Environmental benefits measure the extent to which MC reduced negative environmental impacts throughout the project's lifecycle. This includes emissions, waste generation and resource consumption. 'Economic benefits' refer to the capability of the MC to offer cost efficiency, productivity, early occupancy, faster delivery and a return

Table 1 Sustainability benefits of modular construction

Code	Sustainability impact of MC	Source(s)
ENB	Environment benefits	
ENB01	Minimise carbon emissions	Munmulla et al. [43], Gallo et al. [21], Kamali and Hewage [34]
ENB02	Better building energy efficiency	Chen et al. [10], Kamali et al. [36], Hammad et al. [27], Yang et al. [79],
ENB03	Reduction of construction waste on-site	Yang et al. [79], Chen et al. [10], Kamali et al. [36], Lawson et al. (2012), Kolo et al. [40], Karthik et al. [38], Kamali and Hewage [34]
ENB04	Promote materials reuse and recyclability	Ohiomah and Oguntola, [52]
ENB05	Minimise pollution and offer a neater on-site operations environment	Lawson et al. (2012), Hammad et al. [27]
ENB06	Reduced the embodied energy of building materials	Lawson et al. (2012), Hammad et al. [27], Munmulla et al. [43], Kamali and Hewage [34]
ENB07	Enhance the deconstruction, recovery and reuse of material.	Kamali and Hewage [34]; Nwaki et al. [51]; Ohiomah and Oguntola [52]
ENB08	Enhance the management of materials resources	Nguyen et al. [47], Kamali and Hewage [34]
ENB09	Efficient environmental lifecycle performance	Munmulla et al. [43]; Idris and Adamu [31]; Kamali and Hewage [34]
ECB	Economic benefits	
ECB01	Reduce the cost of labour and equipment on-site.	Hammad et al. [27], Munmulla et al. [43], Idris and Adamu [31]; Nguyen et al. [47], Kamali and Hewage [34]
ECB02	minimise the ordering risks of materials	Gallo et al. [21]; Ohiomah and Oguntola [52]
ECB03	Ease of snag identification and rectification	Wai et al. [72]
ECB04	Reduction in the cost of preliminaries	Kamali et al. [36], Lawson et al. [41]
ECB05	Savings in design and construction cost and time	Kamali et al. [36], Hammad et al. [27], Munmulla et al. [43], Kolo et al. [40], Idris and Adamu [31], Karthik et al. [38], Parracho et al. [59]
ECB06	Faster return on investment (ROI)/chance of early rental income	Lawson et al. [41], Xiong & Baccay (2025)
ECB07	Little or no repair on site (low maintenance cost)	Lawson et al. [41]; Xiong & Baccay (2025)
ECB08	Improve productivity and quality of buildings	Karthik et al. [38], Wai et al. [72], Kamali and Hewage [34]
SOB	Social benefits	
SOB01	Minimise disruption of community activities	Lawson et al.,(2012),Yang et al., [79]; Chen et al., [10]
SOB02	Job creation and crime reduction	Kolo et al., [40]
SOB03	Better working conditions and the safety of workers	Lawson et al. (2012), Fei et al. [18], Yang et al. [79], Chen et al. [10], Kamali et al. [36], Hammad et al. [27], Idris and Adamu [31], Parracho et al. [59], Kamali and Hewage [34]
SOB04	Promote faster housing provision during the disaster period	Wilson (2019),Yang et al. [79]; Chen et al. [10], Parracho et al. [59], Kamali and Hewage [34]
SOB05	Enhance urban resilience	Yang et al. [79]; Chen et al. [10]
SOB06	Minimise inequality and access to urban housing	Yang et al. [79]; Chen et al. [10]
SOB07	Promote social cohesion and inclusivity	Ziaesaeidi and Noroozinejad [82], Jiang et al. [33]

on investment. Social benefits cover the positive impacts of MC and include improved worker safety, community health, and access to housing [51, 62].

1.2.5 Types of SDG contributions in MC

In the assessment of the contribution of MC to sustainable development, it is important to distinguish between different types of contribution.

Direct contributions – Are demonstrated improvements in sustainability outcomes from MC implementation such as reductions in carbon emissions, material waste and improved housing delivery efficiency [27, 34]. These impacts are generally evident at the project delivery stage and are closely related to measurable results related to the SDGs.

Indirect contributions – These occur if MC affects intermediate factors that contribute to the achievement of SDGs, such as increased productivity, resource efficiency, innovation, and improved construction processes [25, 47]. These contributions are often systemic and may occur over longer periods of time.

Policy-aligned contributions – These are those in which the characteristics of MC (e.g. resource efficiency, industrialisation and sustainability-driven design) align with the aims of SDGs 9, 11 and 12, even in the absence of much direct empirical evidence of impact (United Nations, [69, 18]). This reflects MC's alignment with wider sustainability and infrastructure development goals.

Perceived contributions – These are also stakeholder subjective assessments of the extent to which MC contributes to sustainability outcomes. The study was carried out using a questionnaire approach and the findings mainly capture expert opinion in the Nigerian construction sector [5, 77]. Measurable contributions, on the other hand, are based on objective empirical evidence, using quantifiable performance indicators such as cost savings, waste reduction, or environmental performance over a product or system's life cycle [36, 43].

The results of this study are mainly seen as reflecting perceived contributions and policy-congruent contributions, with some link to measurable effects. Hence, the relationships reported are suggestive of stakeholder assessment and alignment with sustainability objectives, but not conclusive evidence of causality or realised SDG impacts.

1.3 Underpinning theories

1.3.1 Innovation diffusion theory (IDT)

Innovation Diffusion Theory (IDT) was first developed by Rogers (1962) to describe the process of how new ideas and technologies are disseminated through a social system over time [65]. According to the theory, five important features influence adoption: relative advantage, compatibility, complexity, trialability, and observability [81]. These characteristics influence stakeholders' decisions to adopt innovative construction methods in the context of modular construction (MC). The most influential of these is relative advantage, which reflects how much better an innovation is perceived to be than the idea it supersedes [65]. MC has clearer benefits compared to conventional production system such as improved safety, improved resource efficiency, less wastage of material, faster delivery, reduced carbon emissions and enhanced quality control [36]. These benefits are very much in line with the objectives of SDGs 9, 11 and 12 on sustainable industrialisation, urban development and responsible production (United Nations, [69]; [18]). Consequently, professionals who are aware of these benefits are more likely to connect MC with achieving these sustainability goals.

This study operationalises IDT by using the concept of relative advantage and the sustainability benefits of MC, captured through the environmental, economic and social dimensions (TBL), as indicators. These perceived benefits influence the stakeholders' assessment of MC's potential contribution to the achievement of SDGs. Hence, IDT

offers a theoretical foundation for the association between perceived sustainability benefits and SDG-oriented perceptions in this study.

1.3.2 The triple bottom line (TBL) theory

TBL thinking is associated with the concept of sustainable development, as the idea is to ensure that meeting today's needs does not deprive future generations of the opportunity to meet their own needs [28]. This theory offers a comprehensive framework for assessing the sustainability performance of innovative tools, techniques, and methodologies [26]. The TBL theory provides organisations with a framework for measuring organisational performance around the sustainability dimensions of economic, social, and environmental [28, 50]. The TBL and sustainability concepts have attracted increased interest among researchers and academics in studies of real estate and construction management. TBL consideration in companies improves sustainability practices for better competitive advantages, improved profitability, better planning for improved efficiency, enhanced decision-making focused on value creation, and a speedy shift from the traditional approach to a more sustainable method – modular construction, modern technologies, climate impact, life cycle assessment, and circular economy practices. Nica et al. [48], Nogueira [50]. These innovations help align business decisions and activities with social, economic and environmental priorities [48]. In the context of this study, the TBL theory provides a framework to anchor the three dimensions of sustainability (i.e., social, economic and environmental) when exploring the impact of adopting MC in housing delivery in a developing economy. Furthermore, the sustainability benefits of MC are operationalised using the TBL framework in three dimensions (economic, environmental, and social), which are the independent constructs used for the empirical analysis.

The IDT provides a construct (relative advantages) of MC over traditional methods, which strongly influences its adoption [83]. MC is an innovative technique (technology) that offers better energy savings and eco-friendly production and can modernise construction more economically compared to the traditional system [24, 46]. TBL provides suitable metrics beyond cost (financial) to include social and environmental metrics for assessing the sustainability of housing delivery. Therefore, TBL is suitable for an overall assessment of sustainability performance in organisations and projects. The sustainability outcomes of adopting MC align with the TBL outcomes and are linked to the selected SDGs 9, 11, and 12, as shown in the hypothetical framework (Fig. 1) below. Further details of the hypothesis development is shown in the next section.

1.4 Hypothesis development

1.4.1 Modular construction vs. SDGs 9, 11, and 12

Ginigaddara et al. [25] define off-site construction (OSC) as the integration of construction and manufacturing processes that deliver buildings manufactured in factories and delivered to the site for erection. They further found that modular construction improves working conditions and helps achieve SDG 8 (decent work and economic growth), SDG 9 (industry, innovation, and infrastructure), and SDG 12 (responsible consumption and production). Furthermore, Off-site construction uses practices that incorporate sustainable materials and renewable energy sources, which support sustainability and align with SDG 11 (sustainable cities and communities) and SDG 13 (climate action). Nwaki

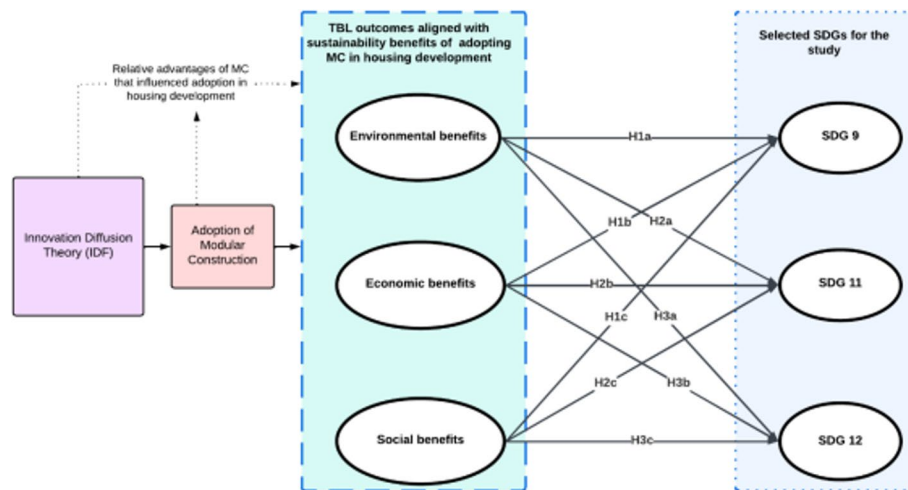


Fig. 1 Hypothetical frameworks for the relationships between MC and selected SDGs. Source: Authors' Conceptualisation

et al.,[51] posit that design for deconstruction (DfD) utilises prefabricated panels/models in building construction, which has implications for minimising resource consumption, the use of technologies, and the provision of speedy housing to meet housing needs caused by population growth and urbanisation. The use of modular components supports achieving the SDGs 9, 11, and 12. MC promotes the adoption of a circular business model in the construction industry, thereby improving the attainment of SDG 11 [12] by enhancing resource efficiency, reducing waste, and fostering sustainable practices that align with urban development goals. Fei et al. [18] posit that the construction industry plays a significant role in achieving the United Nations' 17 SDGs. However, 10 of these SDGs are the most prevalent; among them are SDGs 9, 11, and 12. Hence, their selection in this study.

1.4.2 Modular construction and SDG 9 (Industry, innovation and infrastructure)

SDG 9 seeks to promote sustainable industrialisation, innovation and resilient infrastructure development (United Nations, [69]; [18]). The environmental benefits of MC are mostly associated with SDG 11 and 12, but they also help SDG 9 by allowing resource-efficient industrial production and infrastructure delivery. The MC moves construction away from site-based activities towards controlled factory environments, which improves material optimisation, reduces waste, improves energy efficiency and reduces carbon emissions through standardised processes [10, 47]. These benefits are in line with SDG Target 9.4, which calls for sustainable industrial upgrading. These could increase resource-use efficiency and adoption of cleaner, environmentally friendly technologies.

Moreover, MC employs industrialised processes, automation and lean manufacturing to increase productivity and decrease environmental impacts [21, 56]. The controlled production environment for 3D printing promotes recycling and sustainable material use, and resilient design features enhance the durability of infrastructure [79], all of which contribute to supporting innovation and sustainable infrastructure systems, which are core objectives of SDG 9. Consequently, the hypotheses (H1a-c) are formulated:

H1a: Environmental benefits of MC significantly contribute to the attainment of SDG 9.

H1b: The economic benefits of MC significantly promote the attainment of SDG 9.

H1c: The social benefits of MC significantly contribute to the attainment of SDG 9.

1.4.3 Modular construction and SDG 11 (Sustainable cities and communities)

SDG 11 (Sustainable Cities and Communities): SDG 11 aims to make cities and human settlements inclusive, safe, resilient, and sustainable by 2030 (United Nations, [69]; [18]). Prefabricated building systems led to sustainable urban development by producing less waste and emissions, improving affordable housing and urban development, supporting temporary/emergency housing needs during disasters, and enabling faster urban housing provision with minimal energy consumption [31, 43]. At the construction stage, factory-made building components support SDG11 by reducing costs, enabling faster construction with minimal disruption to neighbours, minimising noise, and requiring fewer on-site materials, particularly in confined urban spaces. These benefits make prefabricated building systems suitable for urban housing developments [10, 78, 79]. These show that there is an association between MC and attainment of SDG 11, and based on these findings, the following hypotheses (H2a-c) are formulated:

H2a: Environmental benefits of MC significantly contribute to the attainment of SDG 11.

H2b: The economic benefits of MC significantly promote the attainment of SDG 11.

H2c: The social benefits of MC significantly contribute to the attainment of SDG 11.

1.4.4 Modular construction and SDG 12 (Responsible consumption and production)

SDG 12 (Responsible Consumption and Production): SDG 12 aims to ensure sustainable consumption and production patterns by 2030 (United Nations, [69]; [18]). The factory-based production approach to prefabricated systems offers improved conditions that promote achieving SDG 12 [25]. MC contributes to the attainment of SDG 12 by improving quality control and resource usage, reducing errors and rework, and promoting the use of green/sustainable and recyclable materials [34, 52, 80]. Furthermore, factory-made components/systems help minimise material waste and support an efficient supply chain, enabling recycling and reusability [34, 37]. Manufacturing in a controlled environment enables contractors to ensure precision in specifications, facilitate just-in-time production, and reuse moulding and casting scans, which helps conserve materials, reduce waste, and lower costs [37], encouraging responsible material consumption and production. Based on this information, the following hypotheses (H3a-c) have been formulated:

H3a: Environmental benefits of MC significantly contribute to the attainment of SDG 12.

H3b: The economic benefits of MC significantly promote the attainment of SDG 12.

H3c: The social benefits of MC significantly contribute to the attainment of SDG 12.

Table 2 presents a summary of the selected SDGs (SDGs 9, 11, and 12) impacted by adopting MC.

Table 2 Selected SDGs impacted by modular construction

Code	Selected SDGs	Source(s)
SDG 9 – Industry, Innovation and Infrastructure		
SDG9-01	Modular construction uses industrialised building techniques and an automated process.	United Nations [69], Gallo et al. [21]; Ouda and Haggag [56], Xiong & Baccay (2025), [59]
SDG9-02	MC minimises on-site activity disruption, utilises lean manufacturing principles, and supports smart infrastructure provisions.	United Nations [69], Gallo et al. [21]; Ouda and Haggag [56], Xiong & Baccay (2025), [59]
SDG9-03	MC supports resilience and scalability due to its shorter building times	United Nations [69], Gallo et al. [21]; Ouda and Haggag [56], Xiong & Baccay (2025), [59]
SDG 11 (Sustainable Cities and Communities)		
SDG11-01	MC led to sustainable urban development by producing less waste and emissions.	United Nations [69], Munmulla et al. [43], Idris and Adamu [31], Xiong & Baccay (2025),
SDG11-02	MC improves affordable housing and urban development	United Nations [69], Xiong & Baccay (2025), Yang et al. [79], Chen et al. [10]
SDG11-03	MC promotes temporary housing to meet disaster needs and supports the provision of faster urban housing with minimal energy consumption.	United Nations [69], Munmulla et al. [43], Idris and Adamu [31], Xiong & Baccay (2025),
SDG 12 (Responsible Consumption and Production)		
SDG12-01	MC offers better quality control, reducing errors, rework, and resource use.	United Nations [69], Yang and Lu [80], Kamali and Hewage [34], Ohiomah and Oguntona [52]
SDG12-02	MC promote the use of green/sustainable and recyclable materials.	United Nations [69], Yang and Lu [80], Kamali and Hewage [34], Ohiomah and Oguntona [52]
SDG12-03	Factory-made components/systems help minimise materials waste and support an efficient supply chain, which allows for recycling and reusability.	United Nations [69], Yang and Lu [80], Kamali and Hewage [34], Ohiomah and Oguntona [52]

1.4.5 Potential constructs overlap and impact on correlation

One potential limitation of this study is the conceptual proximity of the independent and dependent constructs, which could lead to some overlap. The independent variables (environmental, economic and social benefits of MC) are theoretically related to the dependent variables (SDGs 9, 11 and 12), as both are based on the principles of sustainability. For example, environmental benefits such as waste reduction and resource efficiency are closely aligned with SDG 12, whereas social benefits (e.g. improved safety and accessibility) relate to SDG 11. This closeness can lead to overestimation of the observed correlations, due to the shared conceptual domain and not purely on specific relationships.

However, this study addressed this concern by clear operational separation. That is, the benefits of MC are operationalised as project-level sustainability characteristics, while SDG variables operationalise broader development goals oriented towards outcomes (United Nations, [69]; [18]). Thus, the correlations should be interpreted as indicative of perceived alignment rather than causal independence.

1.4.6 Measurement justification for contextual relevance

The measurement items were drawn from existing literature and are deemed relevant in the Nigerian housing context. For example, environmental indicators such as waste and energy efficiency (ENB02, ENB03) reflect important sustainability challenges in Nigeria's resource-constrained construction sector [5]. The economic items of cost savings,

productivity and maintenance reduction (ECB05, ECB08) capture the key concerns in a market characterised by high construction costs and affordability constraints [31]. “Similarly, social indicators like safer working conditions for workers and faster housing delivery (SOB03, SOB04) are in line with the urgent need for safe construction practices and rapid delivery of housing [40].

Therefore, these selected items are theoretically and contextually relevant and justify their validity as indicators of the respective constructs.

2 Research methodology

2.1 Research approach and design

This study adopted a deductive approach guided by a positivist philosophical stance. This approach enables reasonable and reliable conclusions to be drawn from sets of grounds that are true [39], and the method moves from general to specific [73]. The deductive research approach is suitable for survey research designs, and the questionnaire is a satisfactory tool for data collection [66]. These factors informed the choice of the questionnaire to align with the purpose of this study. The questionnaire offers a systematic approach to collecting empirical, quantifiable data from samples and is widely used in the construction management literature, with a focus on modular construction methods and sustainability goals [5, 51].

The questionnaire was designed using Google Forms. The measurement variables (constructs) were obtained and operationalised using multiple factors from the review of relevant literature (see Table 1) and organised following the TBL dimensions and guided by the relative advantage construct of IDT. The adopted questionnaire has three sections. The first section collected data on respondents’ backgrounds and also sought to understand the awareness and adoption levels of MC in house building. These served as a quality check for the information gathered in Sects. 2 and 3. The second section gathered data on the sustainability benefits of MC as independent variables. In this section, participants were asked to rate the importance of the variables’ contributions to housing affordability and sustainability on a 5-point Likert scale, where 1 indicates “very low importance” and 5 indicates “very high importance”. The third section gathered data on the dependent variables - SDGs 9, 11 and 12. These variables were operationalised by selected indicators that corresponded with their core targets (see Table 2). Respondents were asked to indicate their level of agreement with the extent to which modular construction contributes to these SDG-related outcomes, on a 5-point scale, where 1 indicates “very low agreement” and 5 indicates “very high agreement”. The questionnaire was pilot-tested, and variable grouping was validated prior to the primary survey.

Twenty (20) experts were initially identified and participated in a ‘factors categorisation’ validation survey. This survey was meant to (1) determine the applicability of the variables to Nigerian, and (2) the suitability of the variables under each construct. The experts, with considerable experience and knowledge of the subject, were drawn from both academia and industry. The participants were invited to indicate the suitability of the factors under the constructs (environmental, economic, and social) by placing a “No” or “Yes”. In the end, only thirteen (13) submitted their responses, and the results were analysed using the percentage proportion of ‘Yes’ or ‘No’. The proportion of “yes” in each variable confirms their appropriateness in each construct. This process guaranteed that

the measurement items adequately reflect the intended constructs. The participants also confirmed applicability of the variables to the Nigerian context.

2.2 Study population and data collection

Construction professionals (engineers, architects, builders, and quantity surveyors) who work with construction organisations (contractors, consultants, and government-owned organisations) in Abuja and Lagos State, Nigeria, were the targets of this study. These construction experts are at the centre of critical decision-making in the construction industry and the diffusion of innovative techniques and methodologies in the built environment [15]. They are essential for this study. The study selected Abuja and Lagos as its focus due to their status as Nigeria's premier business, construction, and development hubs [3]. Furthermore, it is possible to locate construction experts with better knowledge of modern and advanced construction techniques and methodologies in these areas [16]. Participation in the study was based on criteria such as (1) involvement in off-site/modular construction projects in the areas and (2) having at least 5 years of work/industry experience. It was impractical to obtain a sample frame of experts with these characteristics. Therefore, using random sampling methods became impossible, which informed the use of the non-random methods employed in this study, namely, purposive and snowball sampling. Purposive sampling and snowball sampling are two non-probability sampling methods that are commonly used in construction management research, where the target populations are specialised and difficult to access [2]. Through a preliminary survey, twenty (20) experts with knowledge and experience in the subject were purposively selected to help achieve the study's aim. The researchers contacted the identified experts and invited them to participate in the study by sharing the survey link via their email, WhatsApp, and LinkedIn and professional groups. The cover letter of the questionnaire contains information about the purpose of the study and respondents were required to consent prior to participation. Participation was voluntary and respondents were told that they could withdraw at any time without any negative consequences. Responses were anonymous and confidential, and no personally identifiable info was collected. These initial respondents were requested to refer other qualified experts to the researchers or share the survey with them to drive the snowball sampling method. Respondents drive snowball sampling, which can increase the number of respondents covered, particularly where the sampling criteria make them difficult to reach [17], such as in specialised fields or among hard-to-reach populations, like experts in niche industries.

Several strategies were employed to minimise potential response bias associated with the adopted approach. Firstly, participation was limited to construction professionals with a minimum of 5 years' experience in the construction industry and first-hand knowledge of modular or off-site construction practices. This can help to improve the reliability and quality of the data. Second, the items of the questionnaire were based on existing literature, validated by experts, and tested in a pilot before the main survey to increase clarity, reduce ambiguity, and increase content validity. Third, anonymity and confidentiality of respondents were assured, and no personally identifiable information was collected. This reduced social desirability bias and encouraged honest responses. Fourth, participants were recruited from a range of professional disciplines and organisational categories, which contributed to the diversity of viewpoints and reduced the

potential for homogeneity as seen in the reliability and agreement analyses results. Finally, the lack of very high correlations between the constructs indicates that common method bias was unlikely to have a large effect on the results. This was confirmed by the result of Harman's one-factor test.

2.3 Data screening and methods of analysis

A total of 131 responses were received after a 3-month sampling period. Seven (7) responses were deleted for incompleteness, leaving a total of 124 valid, complete and usable responses (Lagos = 69 (55.65%) & Abuja = 55 (44.35%). The sample size of 124 is considered adequate for non-parametric statistical analysis and in line with sample sizes utilised in similar construction management studies [2]. Cronbach's alpha was used to assess the instrument's reliability, and this yielded Cronbach's alpha ranging from 0.744 to 0.852 for the six constructs (see Table 3). These indicate that the data are reliable and of good quality, as the alpha coefficient exceeds the threshold of 0.70 [17, 57]. The Shapiro-Wilk test was used to establish the normality of the data distribution. The results indicated a significant statistical deviation from normality (p -value < 0.05), which suggest a violation of normality assumption. Thus, justified the use of spearman correlation analysis. Frequency and percentages were used to analyse the respondents' background information and the data on MC awareness and adoption level. The mean score was used to rank the variables (both dependent and independent). Coefficient of variance (CV), Kendall's coefficient of concordance, and chi-square (X^2) were used to assess agreement in the ranking of variables by survey participants. The Spearman correlation (ρ) analysis, an inferential statistical method, was used to establish the strength and direction of association between the independent variables (benefits of adopting MC) and the dependent variables (SDGs), but not causal relationships. The Spearman correlation was chosen for this study because it is effective for assessing the association between ordinal variables and is not restricted to data with a normal distribution, yielding acceptable correlations even with small sample sizes [54]. The use of Spearman correlation to establish relationships between variables in construction and engineering management research

Table 3 Reliability statistics

Constructs		N	%	Cronbach's alpha	N of items
Environment benefits	Valid	124	100	0.793	9
	Excluded	0	0		
	Total	124	100		
Economic benefits	Valid	124	100	0.802	9
	Excluded	0	0		
	Total	124	100		
Social benefits	Valid	124	100	0.852	9
	Excluded	0	0		
	Total	124	100		
SDG9 (industry, innovation and infrastructure)	Valid	124	100	0.794	3
	Excluded	0	0		
	Total	124	100		
SDG11 (sustainable cities and communities)	Valid	124	100	0.744	3
	Excluded	0	0		
	Total	124	100		
SDG12 (responsible consumption and production)	Valid	124	100	0.775	3
	Excluded	0	0		
	Total	124	100		

These demonstrate that the professionals possess the necessary education to understand the questionnaire's content. Finally, 92.74% of the respondents are either corporate or fellow members of their professional bodies. Only 7.26% of them are probationer members of the various professional bodies. These demonstrate considerable professional experience in making a meaningful impact on the study's ability to meet its aim.

3.2 MC sustainability impacts awareness and adoption levels

The results of the response regarding the level of awareness of MC's contribution to sustainability goals, on average, indicate that professionals' awareness is 'very high' (mean = 4.01; proportion = 80.16%). The breakdown in Fig. 3 shows that 73.39% indicated 'high' and 'very high'. Furthermore, the level of practice/adoption of MC in building projects showed a mean of 2.58 (51.61%), indicating a low to very low level of adoption. The results in this section reveal a discrepancy between awareness of the sustainability benefits of MC and its adoption to achieve sustainability objectives. Therefore, more needs to be done in the Nigerian construction industry to adopt sustainable construction methods and achieve the Sustainable Development Goals.

3.3 Descriptive and agreement analysis

The descriptive analysis result in Table 4 showed the relative ranking of the independent and dependent variables. Under the independent variables, the environmental benefits of MC have an overall mean score ranging from 3.97 (79.40%) to 4.31 (86.20%), with an average of 4.15 (82.98%). This indicates that the environmental benefits of adopting MC in housing development have a 'highly important' contribution to sustainability goals. The leading environmental benefits of adopting MC are better building energy efficiency (ENB02) (mean = 4.31), minimise carbon emissions (ENB01) (mean = 4.30), promote materials reuse and recyclability (ENB04) (mean = 4.25), and enhance the management of materials resources (ENB08) (mean = 4.16).

Regarding economic benefits, the means of the variables ranged from 4.00 (80.0%) to 4.23 (84.60%), with an average of 4.10 (81.95%), demonstrating the high importance of these variables in contributing to sustainability in housing production. The top 4 economic benefits are improved productivity and quality of buildings (ECB08) (mean = 4.23), little or no repair on site (low maintenance cost) (ECB07) (mean = 4.15), savings in design and construction cost and time (ECB05) (mean = 4.13), and reduced cost of labour and equipment on-site (ECB01) (mean = 4.08).

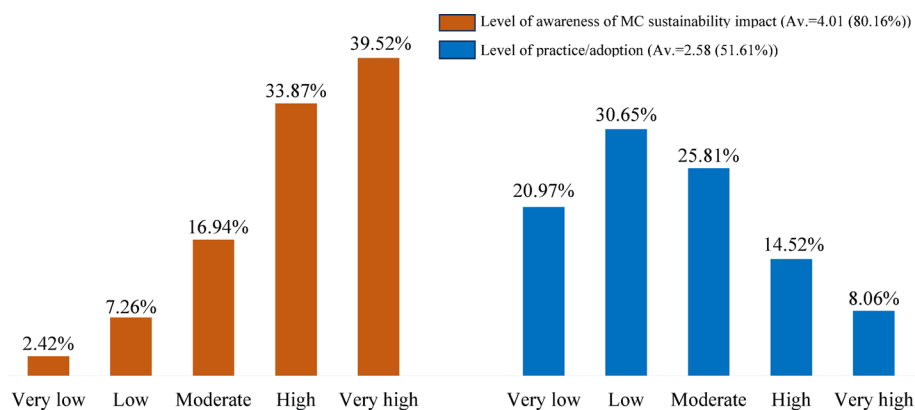


Fig. 3 MC sustainability benefits awareness and adoption levels. Source: Authors' own creation

Table 4 Descriptive statistics results

Constructs	Variable code	Mean	Mean Error	SD	CV	Kruskal-Wallis		RIC	OR
						χ ²	P-value		
Independent variables									
Environment	ENB01	4.30	0.065	0.721	0.168	1.135	0.567	2nd	2nd
	ENB02	4.31	0.067	0.745	0.173	1.822	0.398	1st	1st
	ENB03	4.07	0.084	0.930	0.228	0.803	0.699	7th	17th
	ENB04	4.25	0.072	0.803	0.189	0.007	0.997	3rd	4th
	ENB05	4.09	0.072	0.807	0.197	0.681	0.712	6th	15th
	ENB06	4.16	0.065	0.726	0.174	3.789	0.150	5th	9th
	ENB07	4.03	0.071	0.785	0.195	1.531	0.465	8th	21st
	ENB08	4.16	0.063	0.703	0.169	5.077	0.077	4th	9th
	ENB09	3.97	0.077	0.855	0.215	1.667	0.435	9th	24th
Economic	ECB01	4.08	0.072	0.802	0.197	2.53	0.282	4th	16th
	ECB02	4.07	0.073	0.808	0.198	2.370	0.306	5th	17th
	ECB03	4.00	0.07	0.776	0.194	3.761	0.152	8th	23rd
	ECB04	4.05	0.069	0.764	0.189	1.913	0.384	7th	20th
	ECB05	4.13	0.067	0.743	0.180	2.335	0.311	3rd	13th
	ECB06	4.07	0.073	0.808	0.198	3.530	0.171	5th	17th
	ECB07	4.15	0.082	0.908	0.219	1.401	0.496	2nd	11th
	ECB08	4.23	0.082	0.909	0.215	5.513	0.069	1st	5th
Social	SOB01	4.26	0.069	0.764	0.179	3.191	0.203	1st	3rd
	SOB02	4.21	0.081	0.904	0.215	1.677	0.432	2nd	6th
	SOB03	4.17	0.075	0.833	0.200	7.416	0.025*	4th	8th
	SOB04	4.19	0.071	0.793	0.189	2.725	0.256	3rd	7th
	SOB05	4.15	0.083	0.926	0.223	4.897	0.086	5th	11th
	SOB06	4.03	0.077	0.855	0.212	5.076	0.079	7th	21st
	SOB07	4.11	0.078	0.867	0.211	2.095	0.351	6th	14th
Dependent variables									
SDG 9 – Industry, innovation and infrastructure	SDG9-01	4.23	0.072	0.797	0.188	0.667	0.717	1st	2nd
	SDG9-02	4.07	0.079	0.876	0.215	3.048	0.218	3rd	8th
	SDG9-03	4.12	0.087	0.968	0.235	1.523	0.467	2nd	6th
SDG 11 (sustainable cities and communities)	SDG11-01	4.20	0.083	0.919	0.219	5.095	0.078	1st	3rd
	SDG11-02	4.19	0.081	0.899	0.214	2.175	0.337	2nd	4th
	SDG11-03	4.11	0.085	0.947	0.230	0.949	0.622	3rd	7th
SDG 12 (responsible consumption and production)	SDG12-01	4.36	0.087	0.966	0.221	4.263	0.119	1st	1st
	SDG12-02	4.15	0.082	0.908	0.219	4.501	0.105	2nd	5th
	SDG12-03	4.06	0.098	0.808	0.199	4.198	0.123	3rd	9th
N		124							
Kendall's W		0.019							
Chi-Square (X ²) calculated		79.79							
Chi-Square (X ²) from Table		47.4							
df		33							
Asymp. Sig.		0.000							

*p-value < 0.05; RIC= rank in construct; OR=Overall rank

The social variables have mean values ranging from 4.03 (80.60%) to 4.26 (85.20%), with an average of 4.16 (83.20%), indicating a high importance of the social benefits of adopting MC in housing delivery. The three topmost social benefits of adopting MC are: minimising disruption of community activities (SOB01) (mean = 4.26), job creation and crime reduction (SOB02) (mean = 4.21), and promoting faster housing provision during the disaster period (SOB04) (mean = 4.19).

Overall, notwithstanding the relative ranking of the independent variables across the sustainability pillars, the mean scores ranged from 3.97 (79.35%) to 4.31 (86.13%), with

an average of 4.13 (82.70%), indicating the high importance of these variables in contributing to sustainability goals. The average scores for the sustainability pillars indicate they are highly relevant; however, the social sustainability dimension is the most significant benefit of adopting MC in housing delivery, followed by the environmental pillar and then the economic pillar.

Table 4 also shows the relative rankings of the dependent constructs (SDGs 9, 11, and 12) and their variables. For the dependent variables, the three SDG 9 variables have mean values ranging from 4.07 (81.40%) to 4.23 (84.60%), with an average of 4.14 (82.80%). These indicate strong agreement that adopting MC (modern construction) in housing delivery contributes to achieving SDG 9 (Industry, Innovation and Infrastructure).

Three variables were assessed under SGD 11, and their mean scores ranged from 4.11 (82.20%) to 4.20 (84.00%), with an average of 4.17 (83.33%). These demonstrate strong agreement that MC adoption in housing production contributes to achieving SDG11 (Sustainable Cities and Communities).

Finally, the variables in SGD 12 have mean scores ranging from 4.06 (81.20%) to 4.36 (87.20%), with an average of 4.19 (83.80%). These showed high agreement on the impact of adopting MC in housing development on the attainment of SDG12 (Responsible Consumption and Production).

Overall, regardless of the relative mean weights of the assessed variables and constructs, the mean scores of the dependent variables ranged from 4.06 (81.29%) to 4.36 (87.26%), with an average of 4.17 (83.35%). These indicate a high agreement that MC adoption impacts sustainability goals (9, 11, and 12). Furthermore, the average scores for the constructs (SDGs 9, 11, and 12) indicate that adopting MC in construction has the most significant impact on the attainment of SDG 12, followed by SDG 11 and SDG 9. The topmost four dependent variables, regardless of SDG group, are the following: MC offers better quality control and reduces errors, rework and resource usage (SDG12-01) (mean = 4.36); modular construction uses industrialised building techniques and automation processes (SDG9-01) (mean = 4.23); MC leads to sustainable urban development as it produces less waste and emissions (SDG11-01) (mean = 4.20); and MC improves affordable housing and urban development (SDG11-02) (mean = 4.19).

The standard deviations (SD) of the assessed variables ranged between 0 and 1, indicating a high level of consistency in how the participants rated the variables. Similarly, the standard errors of the means (mean errors) ranged from 0.063 to 0.084 for the independent variables and from 0.072 to 0.098 for the dependent variables. The small sizes of the standard errors imply the reliability and accuracy of the samples. This further means that the variation between the population and the sample mean is negligible. This equally underpins the consistency in responses shown by the SD. The assessed variables have coefficient of variation (CV) values ranging from 0.168 to 0.228 for independent variables and from 0.188 to 0.268 for dependent variables. These show a reasonable degree of agreement (consensus) among the respondents, as the CV values ranged from $0 < CV \leq 0.5$, indicating a “good degree of consensus”. Therefore, the values of the SD, mean errors, and CV confirm consensus among the respondents.

The Kruskal-Wallis test indicates that the assessed variables have p-values ≥ 0.05 , except for SOB03 (better working conditions and the safety of workers), which has a p-value < 0.05 . These results indicate that there is no statistically significant difference in the ratings of the variables by the different participant groups. The statistical difference

observed in SOB03 warrants further reflection. Kendall's $W = 0.019$ indicates a weak level of agreement among the respondents' rankings of the variables, but the associated chi-square (X^2) statistic was statistically significant ($X^2 = 79,788$, $p < 0.001$), indicating that there was consistency observed in the ratings of the variables by the respondents [67]. Although this result does not indicate strong agreement, it is important to note that weak agreement can be statistically significant even in large samples. Therefore, Chi-square results corroborate the findings of the SD, mean errors, and CV regarding consensus among survey participants on the sustainability benefits of MC in Nigeria's construction industry.

3.3.1 Correlation analysis and hypotheses validation

The mean aggregation approach was applied on the indicators under each construct of the independent and dependent variables to obtain the composite construct scores. This was done before executing the correlation analysis. The Spearman correlation analysis results in Table 5 indicate that the rho values range from 0.090 to 0.596, which suggests the absence of multicollinearity in this study. Field, [20] posits that multicollinearity between the assessed variables exists only when the correlation coefficient (rho) exceeds 0.8. Moreover, Harman's single-factor test gave a total cumulative variable explain of 23.385% which is less than the benchmark of 50%, thus, suggests the absence of common method bias (CBM) [29]. The rho ranges from -1.0 to $+1.0$, and the closer it is to 1, the stronger the relationships between the assessed variables. A positive rho value signifies that an increase in the independent variable will lead to a corresponding increase in the dependent variable. When rho is negative, the opposite will hold [1]. The values of rho showed that two hypothetical paths (H1b and H2b) have positive but weak rho values and fall within the scale group of 0.00–0.199. The P-values for these hypotheses were greater than 0.05, indicating insufficient statistical evidence to support the relationships between the economic benefits of adopting MC and SDG9 and SDG11. This indicates

Table 5 Spearman correlation analysis

Path relationship	Kendall's tau_b		Spearman's rho		Remark on Hypothesis	Interpretation of rho
	Correlation coefficient	Sig.	Correlation coefficient	Sig.		
H1b: Economic benefits -> SDG9	0.071	0.296	0.090	0.322	Not supported	Very weak correlation
H2b: Economic benefits -> SDG11	0.105	0.114	0.139	0.122	Not supported	Very weak correlation
H3b: Economic benefits -> SDG12	0.186**	0.005	0.248**	0.005	Supported	Weak correlation
H1a: Environment benefits -> SDG9	0.295**	0.000	0.367**	0.000	Supported	Weak correlation
H2a: Environment benefits -> SDG11	0.333**	0.000	0.420**	0.000	Supported	Moderate correlation
H3a: Environment benefits -> SDG12	0.490**	0.000	0.596**	0.000	Supported	Moderate correlation
H1c: Social benefits -> SDG9	0.370**	0.000	0.454**	0.000	Supported	Moderate correlation
H2c: Social benefits -> SDG11	0.314**	0.000	0.404**	0.000	Supported	Moderate correlation
H3c: Social benefits -> SDG12	0.470**	0.000	0.584**	0.000	Supported	Moderate correlation

**p-value ≤ 0.05 statistically significant difference

a non-significant relationship between MC and SDGs 9 and 11. The hypothetical parts (H3b and H1a) have rho values within the 'weak correlation' range of 0.20-0.399, and their p-values were less than 0.05. Statistically, there is enough evidence to support that there are positive but weak relationships between the economic benefits of MC and SDG12 and between the environmental benefits of MC and SDG9. The rho values for the hypothetical paths (H2a, H3a, H1c, H2c, and H3c) are positive and fall within the 0.40-0.599 range, indicating 'moderate correlation'. In addition, the p-values of these hypothesis paths are less than the 0.05 level of significance. Thus, providing sufficient statistical evidence to support the relationships captured in these hypothetical paths.

3.3.2 Discussion of results

The study revealed that adopting MC can lead to sustainable and affordable housing development. Furthermore, the sampled experts agreed that MC adoption contributes to achieving sustainability objectives, particularly SDGs 9, 11, and 12. The leading sustainability benefits of MC cut across environmental benefits (e.g., better building energy efficiency, minimising carbon emissions, promoting materials reuse and recyclability, enhancing management of material resources, and reduced embodied energy of building materials); social benefits (e.g., minimising disruption of community activities, job creation and crime reduction; promoting faster housing provision during disaster periods; and better working conditions and safety of workers); and economic benefits (e.g., improving productivity and quality of buildings). These findings in Nigeria support existing reports on the impact of MC utilisation in the Chinese construction industry [79] and Sri Lanka [43].

The Spearman correlation analysis indicates that the environmental benefits of adopting MC in housing have a statistically significant impact on the attainment of SDGs 9, 11, and 12. This led to the acceptance of hypotheses (H1a, H2a and H3a). These support the previous report from a cross-national survey [18], a revised-based study [25], and the United Nations [69]. However, while the correlations with SDG 11 and 12 are moderate, they are weak with SDG 9. Notwithstanding the relative strength of correlation coefficients reported on the environmental impact of MC to the selected sustainability goals, the MC techniques are known to contribute significantly to environmental sustainability, with the leading environmental benefits being enhancing building energy efficiency, minimising carbon emissions, promoting materials reuse and recycling and improving materials resource management, thus supporting studies from China [10], Sri Lanka [43], Canada [34] and review-based studies [47].

MC promotes innovation and industrial growth while delivering infrastructure projects [10], thus supporting the attainment of SDG 9 by enhancing the efficiency of resource use and fostering sustainable industrial practices. Modular buildings contribute to the development of sustainable cities by fostering reduced waste and lower emissions, which, in turn, promote community health [43], thereby supporting the achievement of SDG 11. Modular building elements are manufactured in a controlled environment, ensuring better resource utilisation and higher quality while promoting responsible consumption and production (SDG 12). This finding is in line with the report of a global review study [25].

The correlation analysis revealed that the social benefits of MC significantly contribute to the attainment of SDGs 9, 11, and 12, thereby supporting the acceptance of

hypotheses (H1c, H2c, and H3c). The analysis further indicates a positive, significant, and moderate correlation between the MC's social benefits and the attainment of the SDGs 9, 11, and 12. This finding supports existing studies from China [10, 79], Sri Lanka [43] and a cross-national survey of experts from the UK, Ghana, and Hong Kong [18]. MC bolsters innovation through the digitalisation and industrialisation of construction processes. It creates skilled jobs that promote manufacturing and infrastructure resilience, as Kolo et al. [40] found in Nigeria, thus supporting the achievement of SDG 9. The MC technique enables rapid, cost-effective housing production for the community, helping address the pressures of urbanisation and housing affordability [10]. The off-site setting of MC reduces disruption and enhances community health [79] by minimising noise and pollution during construction, which leads to a more pleasant living environment for residents. Thus, the social impact of MC contributes to achieving SDG 11. MC supports circular economy practices by enabling the deconstruction and repurposing of modular units, which promote resource efficiency and reduce inequality and access to urban housing, as Yang et al. [79] found in China and Ziaesaeidi and Noroozinejad and [82] found in a cross-national comparative study of Canadian and Iranian experts. Therefore, adopting MC contributes to SDG 12 by improving social impact.

This study found that the economic benefits of MC have weak and statistically non-significant correlations with SDGs 9 and 11. However, despite the high ratings of key economic benefits such as improved productivity and quality (ECB08), reduced maintenance costs (ECB07), savings in cost and time (ECB05) and reduced labour costs (ECB01), these did not translate into significant contributions to SDG 9 ($p = 0.090$; $p = 0.322$), or SDG 11 ($p = 0.139$; $p = 0.122$). The only significant but weak relationship was with SDG 12 ($p = 0.248$; $p = 0.005$). This suggests that economic benefits alone may not be enough to produce wider effects in industry innovation, infrastructure development and sustainable urbanisation. One important reason is the poor level of uptake of MC, despite high levels of awareness. The awareness of the benefits of MC was quite high (mean = 4.01) but the actual adoption was low (mean = 2.58) which suggests that the economic benefits are more perceived than realised in reality [5, 77]. This limits their observable influence on SDG outcomes. These findings do not align with research from the mature market of Canada [36] and emerging market of Sri Lanka [43] which indicate significant economic benefits.

In addition, the economic advantages of MC depend on economies of scale, standardisation and an established industrial basis. The growth of MC in Nigeria is still in its infancy and will require a substantial initial investment in production plants, logistics and skills acquisition. Such investments will not deliver the projected cost savings without adequate market demand [3, 31]. Moreover, the limited local manufacturing capacity, dependence on imported materials and components, fragmented supply chains and low standardisation hinder operating efficiency and increase cost. Limited market potential due to the lack of supportive governmental frameworks and incentives also makes MC implementation commercially unfeasible [3]. Overall, the results suggest that environmental and social benefits are more promising avenues for Nigeria's SDG achievement, whereas economic benefits depend on structural and institutional improvements.

Finally, the results confirm the importance of the TBL framework, since the environmental and social dimensions are more closely related to SDG achievement than the economic dimension. This suggests a multidimensional but uneven sustainability

performance of MC across TBL pillars, indicating that while some areas may excel in sustainability, others lag behind, highlighting the need for targeted improvements in the weaker dimensions. The results are further supportive of IDT, suggesting that perceived benefits of MC (i.e., relative advantage) are critical in facilitating its adoption and alignment with sustainable development outcomes.

However, even with the identified benefits, MC is not without its challenges. Its high initial capital investment, the need for specialised manufacturing facilities, and limited technical expertise may limit its widespread adoption, especially in developing countries. Furthermore, some of the perceived benefits may be offset by supply chain constraints and resistance to change among industry stakeholders, which can hinder the effective implementation of MC practices in various sectors. These trade-offs may explain the non-significant influence of economic benefits in this study. These trade-offs are also evident in the results, which reveal that the sustainability impacts of MC in the housing sector are not uniform across all dimensions. The environmental and social benefits have stronger relationships with SDG attainment than economic benefits, indicating that prioritising these aspects may lead to more effective outcomes in achieving sustainable development goals in the housing sector.

3.3.3 SDG-driven decision-making framework for modular construction

Based on the literature review and statistical analysis results and findings of this study, an SDG-based framework for construction stakeholders' decision-making for MC adoption in housing production is developed (Fig. 4). The framework integrates SDG outcomes (SDGs 9, 11, and 12) for adopting MC and sustainability dimensions (economic, environmental, and social) based on the variables and empirical results reported in this study. The framework is organised into six stages: input, evaluation, relationship overview, decision-making, outcome alignment and application.

The framework identified weak (weak supported), non-significant (unsupported) and significant (moderately supported) relationships to enable construction businesses and stakeholders to prioritise the dimensions that have high impact on sustainability attainment. The findings indicate that the sustainability impact of MC adoption in housing production varies, with stronger and significant contributions arising from environmental and social benefits, whereas the influence of economic benefits on SDGs is non-significant.

Policymakers and industry practitioners could practically use the framework to guide resource allocation, strategy selection, and performance monitoring. The framework supports evidence-based decision-making, but it is based on correlational data and should be applied in the context of contextual factors.

3.3.4 Implications of the study

This study makes a significant contribution to theory and practice. One of the theoretical contributions of the study lies in combining TBL and IDT to explain how sustainability benefits of MC impact SDG attainment in a developing country context. This study adds to the growing body of knowledge on the critical role of the construction industry in the achievement of the United Nations Sustainable Development Goals (SDGs) by 2030. The study empirically establishes significant relationships between the benefits of modular construction (MC) adoption and SDGs

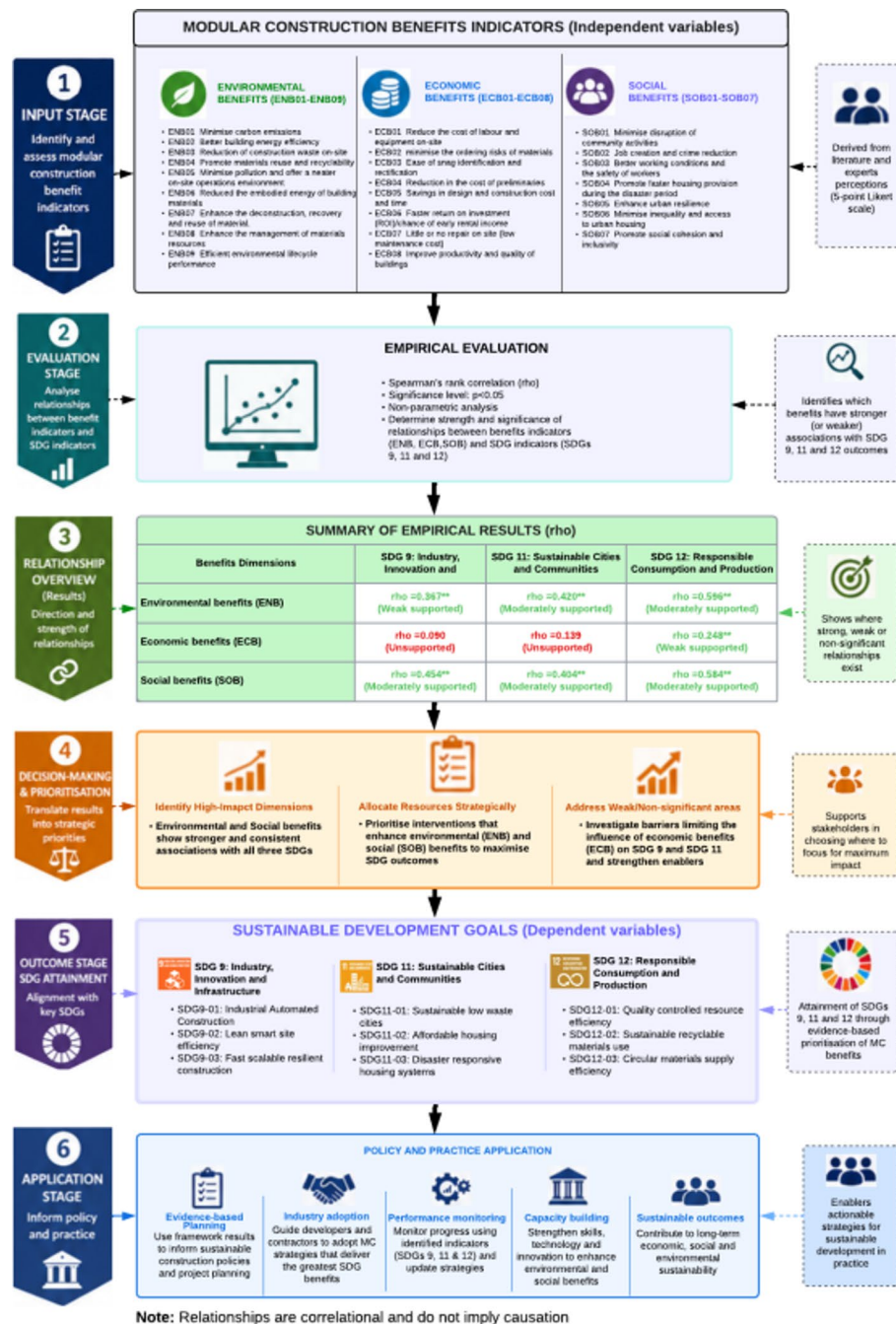


Fig. 4 SDG-driven decision-making framework for MC. Source: Authors' own creation

9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production), showing how construction innovations can be measurable pathways to sustainable development. MC plays a strategic role in sustainability discourse, as our findings demonstrate. Our findings add to the existing literature by connecting the benefits of MC adoption to specific SDG targets in the context of a developing country. The study therefore offers a strong empirical foundation for future research aimed at examining

construction-driven contributions to SDG achievement, especially in emerging economies struggling with systemic housing and infrastructure issues.

The study offers practical suggestions for policymakers, industry stakeholders and educational institutions to enhance the delivery of affordable, comfortable, and environmentally sustainable housing in Nigeria and other developing countries. The results highlight the importance of governments introducing incentive-based policies, such as tax rebates, public procurement preferences, and green certification credits, to encourage the adoption of modular construction. Embedding MC in policies for national housing and infrastructure development can facilitate uptake and position the housing sector to support SDGs 9, 11 and 12, particularly in the early stages of planning and procurement.

Industry unions and professional associations are urged to develop awareness programmes, training workshops, and capacity-building initiatives to improve practitioners' understanding of modular systems, quality control processes, and their lifecycle benefits. These initiatives can help reduce resistance to MC adoption, as well as the perceived risks and complexity discussed in previous studies (Akinradowo et al. 2023). Furthermore, the development of national standards and guidelines for modular design, manufacture, and assembly will contribute to quality assurance, cost-effectiveness, and investor confidence, thus facilitating the large-scale deployment of MC techniques [76].

The study also stresses the importance of multi-stakeholder collaborations between government agencies, developers, professional bodies, and research institutions to foster innovation, data sharing, and pilot projects that demonstrate the economic, social, and environmental benefits of modular housing. This collaborative effort across planning, production, and delivery is essential for establishing an ecosystem conducive to the adoption of modular construction (MC). It aims to address housing shortages and promote sustainability objectives in both developing and established construction markets. Finally, the education sector can use the study's findings to integrate SDGs and MC principles into the higher education curricula to enhance sustainability literacy and technical competence in built environment graduates.

4 Conclusion and recommendations

This study, through a questionnaire survey, assessed the sustainability benefits of MC techniques in housing provision. Empirical data were collected from construction experts using purposive and snowball sampling techniques, and the gathered data were analysed using descriptive statistics tools and Spearman's correlation coefficient. The findings lead to the following conclusions.

The study reveals that adopting MC in housing production in the construction industry makes a significant contribution to sustainability in housing development. The descriptive analysis results indicated that the most important contribution of MC adoption in housing delivery is on the social sustainability pillar, with the leading social benefits being minimising disruption of community activities (SOB01), job creation and crime reduction (SOB02), and promoting faster housing provision during the disaster period (SOB04).

The second most important benefit of adopting MC in housing delivery is environmental sustainability. The leading benefits are 'better building energy efficiency (ENB02);

‘minimise carbon emissions (ENB01)’, ‘promote materials reuse and recyclability (ENB04)’, and ‘enhance the management of materials resources (ENB08)’.

The study revealed that the economic sustainability pillars are the third significant benefit of adopting MC in housing production. The leading benefits are ‘improved productivity and quality of buildings (ECB08)’, ‘low maintenance cost (ECB07)’, ‘savings in design and construction cost and time (ECB05)’, and ‘reduction of labour and equipment cost on-site (ECB01)’.

Furthermore, the descriptive analysis revealed that the sampled experts strongly agreed that adopting MC has a substantial impact on achieving the SDGs 9, 11, and 12. Based on overall mean scores, adopting MC in construction has the most significant impact on achieving SDG 12, followed by SDG 11 and SDG 9.

Furthermore, the correlation analysis indicates that adopting MC in construction has a positive, statistically significant relationship with achieving the SDGs 9, 11, and 12. While the environmental benefits are positively associated with SDGs 11 and 12, their impact on SDG 9 is weak; however, they exhibit a moderate correlation with SDGs 11 and 12. The results also indicated that the social impact of adopting MC in construction is positive, yet moderate and statistically significant, in relation to achieving the SDGs 9, 11, and 12. The economic benefit of adopting MC in housing production was found to have a very weak positive correlation, non-statistically significant, with the attainment of SDGs 9 and 11. However, the results indicated a weak, positive, and statistically significant relationship with the attainment of SDG 12. However, the adoption of MC techniques could be limited by technical, economic, and institutional conditions that need further attention, such as inadequate training for workers, high initial costs, and regulatory barriers that hinder implementation. These constraints could be responsible for the variations observed in the impact of MC across the sustainability dimensions, particularly in how different sustainability goals are prioritised and addressed in various contexts.

While the study’s significant contributions are enormous, it has its limitations, which should serve as a caution when interpreting and generalising the findings. The results do indicate strong linkages between perceived sustainability benefits of MC and SDG-related outcomes but are not direct measures of SDG accomplishment. Actual contributions to SDGs 9, 11 and 12 would require longitudinal performance data, lifecycle assessments, project-level sustainability metrics or national SDG indicator datasets. Thus, the results are best interpreted as evidence of perceived and policy relevant contributions that could support sustainable development objectives if implemented effectively in the housing sector. The study’s sample size, settings, methods and approaches are limitations that future studies should overcome. Future studies could collect more samples, employ mixed-methods, and adopt probabilistic sampling techniques and fuzzy set theory to refine the contribution of MC adoption within each assessed benefit category. The findings offer context specific to Nigeria and other developing countries with similar institutional, technological and economic conditions. Future research can address this limitation by considering more states, regions, or other developing countries. This study will provide data for comparison. Abuja and Lagos offer a better choice for this study because of the concentration of construction organisations and professionals with greater exposure to innovative sustainable techniques and methodologies, which may have introduced

some urban bias associated with industrialised settings. This should guide the scientific community in generalising the findings to other less developed Nigerian construction markets. Future research endeavours should extend data collection to other states and regions to capture more diverse contexts and underpin the generalisability of the outcomes. In addition, similar studies could be undertaken in developed countries with stronger interests and policies in the sustainability agenda to determine whether the outcomes will be similar or different. Non-probabilistic (purposive and snowball sampling) methods used in this study may have introduced some sampling bias due to the selection of experts based on their accessibility and professional networks and not randomly. This could limit sample representativeness and the generalisability of findings to the wider construction industry in Nigeria. These techniques were judged as appropriate given the lack of a comprehensive sampling frame and the need to target professionals with relevant experience of MC. To overcome the sampling limitations, future studies could use probabilistic sampling methods to strengthen external validity. Although these limitations are present, the considerable experience of the experts (average 14 years of experience), increases the credibility and reliability of the responses.

A cursory look at the values of the standard deviation (SD), mean errors, and coefficient of variation (CV) confirms the respondents' genuine consensus. Furthermore, the results of the Kruskal–Wallis and Kendall's Coefficient of Concordance tests supported the genuine consensus, indicating that there were no statistically significant differences among study participants' responses. Although no statistical evidence suggests that any single network influenced the findings, this limitation should guide the interpretation of this study's outcome. The use of correlational analysis limits the causal inference between the benefits of MC and the achievement of the SDGs. Future studies could consider longitudinal designs and structural equation modelling (SEM) to look at causal pathways. This study established a relationship between MC adoption and the SDGs 9, 11, and 12. The study's focus on these three sustainability goals limits the potential to establish relationships with other Sustainable Development Goals (SDGs). Therefore, future studies could incorporate the contribution of MC to SDG 13 (Climate Action), SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), SDG 3 (Good Health and Well-being), and SDG 7 (Affordable and Clean Energy). The dearth of studies in this area constitutes a significant research gap that warrants further investigation.

Supplementary Information

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Supplementary Material 1

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Author contributions

G.O: Conceptualisation, Literature review, discussion of results, review and editing of initial draft, and project management E.E: Conceptualisation, methodology, analysis, review and editing of the initial draft, Supervision and project management. M.Z: Methodology, data collection, drafting and review of the manuscript A.A: Methodology, data collection, drafting of manuscript, and initial review and editing of draft. The final manuscript was read and approved by all the authors.

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Data availability

The datasets collected and analysed in this study are available from the corresponding author upon reasonable request.

Declarations**Ethics approval and consent to participate**

The requirement for ethical approval was waived by the Ethics Committee of the Department of Quantity Surveying, Federal University of Technology Owerri, in accordance with the University's Institutional Research Ethics Policy and the principles of the Declaration of Helsinki. Informed consent was obtained from all participants before their involvement in the study. Participation was voluntary, and respondents were informed of their right to withdraw at any stage without penalty. Confidentiality and anonymity were assured throughout the research process, and no sensitive personal or identifiable information was collected. Informed consent was obtained from all participants prior to their participation in the study. Participation was voluntary, and respondents were assured of the confidentiality and anonymity of their responses.

Consent for publication

Not applicable as no identifiable data or images are present within the manuscript.

Competing interests

The authors declare no competing interests.

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