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| RESEARCH ARTICLE

Evaluation of Spatial Adequacy Benchmark in Sustainable Maritime Operations in Nigeria

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| ABSTRACT

Spatial adequacy benchmarks constitute a critical foundation for sustainable maritime operations, as they ensure efficient utilization of maritime spaces, enhance safety, and promote environmental and operational sustainability. This study evaluate spatial adequacy benchmark in sustainable maritime operations in Nigeria. Five objectives and five research questions were formulated and answered respectively in this study. Data was generated from 312 respondents, comprising of port managers, marine engineers, maritime safety officers, terminal operators, shipping company personnel, port planners, logistics and supply chain managers and maritime regulatory officials using researchers' developed questionnaire titled "Spatial Adequacy Benchmark and Sustainable Maritime Operations Questionnaire (SABSMOQ)." Using descriptive statistics to analyze the data generated for the study, the researchers found out that berth length and occupancy rate, navigational channel width and depth, terminal storage yard capacity, vessel maneuvering and turning basin spaces, and intermodal access corridors with logistics support spaces are widely applied in assessing the adequacy of maritime infrastructure and ensuring efficient and sustainable maritime operations. Again, berthing facilities, navigational channels, storage areas, logistics spaces, and supporting infrastructure generally provide adequate capacity for maritime operations. Findings also revealed that spatial adequacy has a significant positive effect on environmental sustainability in maritime operations. Also, the study show that the attainment of spatial adequacy in maritime operations in Nigeria is hindered by inadequate investment in port infrastructure expansion, increasing cargo and vessel traffic, poor implementation of maritime spatial planning policies, limited waterfront land availability and urbanization pressures, as well as bureaucratic and regulatory inefficiencies. Finally, the key measures that can be adopted to improve spatial adequacy benchmarks for sustainable maritime operations in Nigeria include increased investment in port infrastructure expansion and modernization. Based on the findings of this study, the researchers concluded spatial adequacy remains a fundamental prerequisite for achieving operational efficiency, environmental sustainability, and safety in maritime operations, while inadequate spatial provision poses a significant threat to the long-term sustainability of Nigeria's maritime sector. Consequently, the researchers recommended for increased investment in maritime infrastructure, strengthening spatial planning policies, as well as expansion of port and logistics facilities.

| KEYWORDS

Berthing facility, storage area, spatial adequacy benchmark, maritime operation

| ARTICLE INFORMATION

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1. Introduction

Spatial adequacy benchmark means having enough physical space, infrastructure, and coverage for maritime operations. In other words, it implies the sufficiency of physical and operational space within ports, terminals, waterways, and associated maritime infrastructure to accommodate vessel traffic, cargo handling activities, storage requirements, intermodal connections, and future growth demands. It serves as a critical benchmark for evaluating whether maritime facilities possess the capacity and spatial configuration necessary to support efficient, safe, and sustainable operations. Spatial adequacy encompasses berth length, channel width and depth, storage yards, terminal layouts, navigational spaces, equipment positioning, and hinterland connectivity. The concept is closely linked to operational efficiency, safety, environmental sustainability, and economic competitiveness, (Vesel, O'Connor and O'Shaughnessy, 2023).

Spatial adequacy impact on maritime operations in terms of surveillance and response, decongestion, access control and assert deployment. Adequate port space, radar coverage, and patrol zones enable monitoring of vessels and faster response to threats like piracy or smuggling. Again, sufficient berths and anchorage reduce vessel clustering, lowering collision risk and making illegal activities harder to hide. Furthermore, properly spaced facilities allow effective check pointing and inspection, blocking unauthorized entry. Finally, enough spatial capacity ensures naval/coast guard assets can be positioned strategically for deterrence. Without spatial adequacy, blind spots and bottlenecks emerge, weakening security enforcement.

According to contemporary port planning literature, spatial adequacy is not merely a function of physical dimensions but also of the ability of maritime infrastructure to support current and projected operational demands without causing congestion, delays, or environmental degradation. Vesel, O'Connor and O'Shaughnessy (2023) also posited that as maritime trade volumes continue to grow globally, ports are increasingly required to adopt scientifically established spatial benchmarks to ensure sustainable operations.

According to Theofanis, Boile and Golias (2009), one of the most widely used spatial adequacy benchmarks is berth capacity. Berths constitute the primary interface between ships and ports, making their adequacy essential for efficient operations. Berth adequacy is commonly assessed through indicators such as berth length, berth occupancy ratio, vessel waiting time, and vessel turnaround time. Research suggests that excessive berth occupancy rates often result in congestion and operational inefficiencies, while adequate berth provision enhances throughput and service quality. Recent studies such as Ismail, Joel and Lekan (2025) have further demonstrated that berth characteristics, including length, depth, and accessibility significantly influence port performance and cargo handling efficiency. Ports with inadequate berth dimensions often experience vessel delays and increased logistics costs.

Nautical access refers to the spatial adequacy of waterways, channels, turning basins, and approach routes. Vesel, O'Connor and O'Shaughnessy (2023) stated that benchmarks in this area focus on channel depth, channel width, turning circle dimensions, and navigational clearance. Adequate navigational space enables safe vessel movement, reduces collision risks, and supports larger vessels. Port capacity studies such as Bassan (2007) identified nautical access as one of the most critical components of spatial adequacy because it determines the size and frequency of vessels that can access port facilities. Inadequate navigational space can significantly constrain operational capacity regardless of berth availability.

Storage and terminal yard capacity represent another major dimension of spatial adequacy. Newton, João, Rui and Afonso (2017) noted that terminal yard and storage space benchmarks commonly evaluate storage area per cargo volume, yard utilization rates, stacking density, and cargo dwell times. Adequate storage space is necessary to prevent congestion and ensure smooth cargo flow between maritime and land transport systems. Studies on port terminal capacity emphasize that insufficient yard space often becomes a major operational bottleneck, limiting throughput even when berthing facilities are adequate. Effective spatial planning therefore requires balancing berth capacity with corresponding storage infrastructure.

Spatial adequacy extends beyond port boundaries to include road, rail, and inland waterway connections. Yunianto, (2025) asserted that existing benchmarks assess the availability and efficiency of intermodal infrastructure linking ports to hinterland markets. Indicators include road capacity, rail access, cargo transfer facilities, and logistics corridor performance. Research such as Ceylan et al. (2026) indicated that adequate land space and intermodal connectivity are essential for minimizing cargo congestion and enhancing overall maritime logistics performance. Ports lacking sufficient hinterland infrastructure frequently experience operational inefficiencies despite having adequate marine facilities.

Vesel, O'Connor and O'Shaughnessy (2023) upheld that port capacity planning benchmarks evaluate whether existing infrastructure can accommodate future demand. These benchmarks include throughput capacity, vessel handling capacity, utilization rates, and expansion potential. Modern port planning increasingly employs simulation models and capacity forecasting techniques to determine whether available space can support projected growth. Simulation-based studies reveal that sustainable maritime operations require continuous assessment of berth capacity, storage facilities, truck gates, and operational spaces to ensure alignment with expected traffic growth. , (Olba, Daamen, Vellinga, and Hoogendoorn, 2021).

Recent developments in maritime sustainability have expanded traditional spatial adequacy benchmarks to include environmental considerations. According to Chang, Tongzon, Luo, and Lee (2012) stated that these benchmarks evaluate the availability of green infrastructure, emission reduction facilities, alternative fuel storage, energy-efficient terminal layouts, and environmental buffer zones. Contemporary sustainable port frameworks emphasize that spatial adequacy should not only support operational efficiency but also facilitate environmental protection, climate resilience, and decarbonization objectives. Sustainable maritime infrastructure therefore incorporates both economic and environmental dimensions of space utilization.

Although numerous benchmarks exist, the literature reveals several limitations. For instance, Olba, Daamen, Vellinga, and Hoogendoorn, 2021 made three critiques on spatial adequacy benchmarks. First, there is no universally accepted framework for measuring spatial adequacy across different port types and operational contexts. Benchmark standards often vary according to cargo characteristics, vessel sizes, geographic conditions, and regulatory environments. Second, many traditional benchmarks focus primarily on physical infrastructure dimensions while neglecting operational dynamics, technological advancements, and sustainability considerations. Modern ports increasingly require integrated assessment approaches that account for digitalization, automation, environmental performance, and resilience. Third, existing studies indicate that capacity assessment methodologies frequently lack standardization, making comparative evaluation across ports difficult. Consequently, there remains a need for comprehensive frameworks that integrate operational efficiency, safety, environmental sustainability, and future adaptability into spatial adequacy assessment.

Ismail, Joel and Lekan (2025) conducted a study to examines how various berthing factors such as the number of berths, quay length, maximum depth, operational areas, and cargo-specific zones affect the performance of four major Nigerian seaports; Tin Can Island, Apapa, Onne, and Delta. The study analyzed data from 367 respondents using descriptive and inferential statistics. The findings show that while the existing number of berths largely meets traffic demands, congestion occurred during peak periods, highlighting capacity limitations. Quay length was identified as a major determinant of efficiency, longer quay enhances vessel handling and reduce delay. Maximum berth depth was adequate for most operations but emphasized the need for deeper berths to handle larger vessels with high draft requirements. Regression analysis revealed that berth depth, quay length, operational area, management style, dedicated areas, investment in berth infrastructure, and number of berths collectively explained 65.2% of the variability in performance of seaport.

Mehmet (2026) developed a systems-based decision framework to prioritize sustainable port management measures within the framework of the 2023 International Maritime Organization (IMO) Greenhouse Gas (GHG) Strategy and Annex 15. Using an integrated DEMATEL–ANP approach, causal relationships among nineteen port-level measures were identified, and their relative priorities were systematically evaluated across five dimensions: infrastructural transformation, global port development, capacity building, inter-sectoral collaboration, and green and low-carbon innovation. The DEMATEL results reveal that governance and collaboration clusters exert the strongest causal influence on the network, while financial and technical support mechanisms act as key driving enablers. The ANP results indicate that port modernization for GHG reduction, storage capacity for low-carbon fuels, and joint emission reduction programmes hold the highest overall priorities, reflecting their systemic leverage in accelerating port-level decarbonisation.

Mehrnaz, Michele,Tony, Walkera, and Magnanc (2019) assessed the current state of corporate sustainability in ports in Canada and the US. The study ascertained the perception of port executives towards sustainability, analyzed port sustainability strategies and practices, and identified the main factors (motivations/driving factors and key challenges/barriers) influencing future adoption and implementation of corporate sustainability in ports. Results show that the majority of ports perceive sustainability as important and have adopted a number of sustainability strategies and practices, such as sustainability awareness and training programs, sustainability reporting, and sustainability initiatives and standards (e.g., Green Marine and ISO 14001 certification). Results also show that sustainability strategies have resulted in improved stakeholder relations in ports mainly with government/policy makers, customers, local communities, and industry associations. Again, findings from this study indicated that although corporate sustainability is regarded as important in the majority of ports, it is not fully integrated in strategic decision-making processes and operations in most ports.

Odette (2025) explored the technological gaps and sustainability performance of the world's 50 major ports from 2000 to 2023, motivated by increasing global environmental pressures and the uneven adoption of green technologies. Using the Stochastic Frontier Analysis within a Meta-frontier framework, the study evaluates port efficiency relative to both group-specific and global best-practice frontiers. Results show that ports in Cluster 1 (Singapore, Shanghai, Busan) exhibit the highest levels of efficiency and no technological gaps, due to strong infrastructure investment, low CO_2 emissions, and effective sustainability strategies. In contrast, ports in Clusters 3 and 4 lag significantly behind, constrained by operational inefficiencies and inadequate adoption of clean technologies. The study concludes that to enhance port competitiveness, strategic investment in green infrastructure, stronger sustainability policies, and targeted workforce training are essential. This research provides empirical evidence to guide global port modernization, policy formulation, and environmental transition.

Spatial adequacy benchmarks originate from maritime infrastructure planning principles that emphasize the relationship between available space and operational performance. These benchmarks provide measurable standards against which the capacity and effectiveness of maritime facilities can be assessed. The underlying assumption is that maritime operations become inefficient when infrastructure capacity falls below operational demand and wasteful when capacity significantly exceeds demand. Therefore, spatial adequacy benchmarks seek to establish an optimal balance between infrastructure provision and operational requirements. Port planners traditionally employ benchmarks based on vessel dimensions, cargo throughput, berth occupancy rates, storage capacity utilization, navigational safety requirements, and intermodal accessibility. These indicators facilitate informed decision-making regarding port expansion, modernization, and resource allocation.

The literature demonstrates that spatial adequacy benchmarks constitute a fundamental tool for evaluating maritime infrastructure performance and sustainability. Existing benchmarks primarily focus on berth capacity, navigational space, storage facilities, land availability, intermodal connectivity, and overall port capacity. Recent developments have expanded these benchmarks to include sustainability and environmental performance indicators. However, the absence of a universally accepted assessment framework and the limited integration of sustainability dimensions reveal significant gaps in existing knowledge. These gaps justify the need for empirical evaluation of spatial adequacy benchmarks and their effectiveness in promoting sustainable maritime operations.

1.1 Statement of the Problem

The maritime sector remains a critical driver of global trade, economic development, and regional integration. As maritime activities continue to expand in scale and complexity, the demand for adequate spatial infrastructure, including berthing spaces, navigation channels, cargo handling areas, storage facilities, intermodal connections, and operational layouts, has become increasingly important. Spatial adequacy constitutes a fundamental benchmark for ensuring efficient, safe, environmentally responsible, and sustainable maritime operations. Consequently, international maritime standards and best practices emphasize the need for optimal utilization and allocation of maritime space to support growing operational demands while minimizing environmental and operational risks.

Despite significant investments in maritime infrastructure across many countries, concerns persist regarding the adequacy of available operational spaces to accommodate increasing vessel traffic, cargo volumes, and associated logistics activities. In many ports and maritime facilities, congestion, limited berth capacity, inadequate storage areas, inefficient traffic circulation, navigational constraints, and poor spatial planning have continued to undermine operational performance. These challenges often result in increased vessel turnaround times, reduced cargo throughput efficiency, higher operational costs, safety hazards, and environmental degradation, thereby compromising the sustainability of maritime operations.

Furthermore, while considerable attention has been devoted to maritime infrastructure development, less emphasis has been placed on evaluating whether existing spatial provisions meet established adequacy benchmarks necessary for sustainable operations. Existing studies have largely focused on port efficiency, logistics performance, maritime safety, and environmental management, with limited empirical evidence on the extent to which spatial adequacy benchmarks influence sustainable maritime operations. This creates a knowledge gap regarding the appropriateness of current spatial configurations and their effectiveness in supporting operational productivity, environmental sustainability, and safety objectives within the maritime sector.

Moreover, the absence of systematic evaluation frameworks for assessing spatial adequacy has made it difficult for policymakers, port authorities, and maritime operators to identify deficiencies and implement evidence-based improvements. Without a clear understanding of the relationship between spatial adequacy and sustainable maritime operations, efforts aimed at enhancing maritime competitiveness and sustainability may remain ineffective or inadequately targeted. It is against this backdrop that this study seeks to evaluate spatial adequacy benchmarks in sustainable maritime operations by assessing the extent to which existing maritime facilities conform to established spatial standards and examining their influence on operational efficiency, environmental sustainability, and safety performance. The study is expected to provide empirical evidence that will support informed decision-making and contribute to the development of more sustainable and efficient maritime systems.

1.2 Objectives of the study

The aim of this study is to evaluate the adequacy of spatial benchmarks in promoting sustainable maritime operations. Specifically, the study will achieve the following;

1. To assess the existing spatial adequacy benchmarks applied in maritime operations.
2. To determine the extent to which available maritime spatial infrastructure meets operational requirements.
3. To evaluate the effect of spatial adequacy on environmental sustainability in maritime operations.
4. To identify challenges associated with achieving spatial adequacy in sustainable maritime operations.
5. To determine appropriate strategies for improving spatial adequacy benchmarks that enhances sustainable maritime operations.

1.3 Research Questions

The following research questions were posed and addressed in this study;

1. What spatial adequacy benchmarks are currently utilized in maritime operations?
2. To what extent do existing maritime spatial facilities and infrastructure satisfy operational requirements?
3. What effect does spatial adequacy have on environmental sustainability in maritime operations?
4. What challenges hinder the attainment of spatial adequacy in maritime operations?
5. What measures can be adopted to improve spatial adequacy benchmarks for sustainable maritime operations?

2. Methodology

This section provides the various methods used in this study as well as the philosophy, logic and rationality for using the methods.

2.1 Research Design

This study adopts a descriptive survey research design complemented by an evaluative research approach. The descriptive survey design is considered appropriate because it enables the researcher to obtain data from maritime stakeholders regarding the adequacy of existing spatial benchmarks and their implications for sustainable maritime operations. The evaluative approach facilitates the assessment of the extent to which existing maritime spatial infrastructures conform to established spatial adequacy standards and sustainability requirements. The design is suitable for generating empirical evidence on the relationship between spatial adequacy benchmarks and sustainable maritime operations.

2.2 Area of the Study

The study is conducted within selected maritime operational environments, including seaports, terminal facilities, shipping channels, logistics hubs, and maritime support infrastructures. The geographical scope covers major maritime operational zones where shipping, cargo handling, vessel navigation, and port logistics activities are undertaken. These locations are selected because they provide relevant data for assessing spatial adequacy benchmarks in maritime operations.

2.3 Population of the Study

The population of the study comprises all stakeholders involved in maritime operations, planning, regulation, and management. These include port managers, marine engineers, maritime safety officers, terminal operators, shipping company personnel, port planners, logistics and supply chain managers and maritime regulatory officials. Given the dynamic nature of maritime operations and the absence of a comprehensive sampling frame covering all maritime stakeholders, the population is considered large and indeterminate.

2.4 Sample size and sampling technique

The sample size of this study was initially determined using Cochran (1977) formula for an infinite population, which yielded 384 respondents. To accommodate non-response and incomplete questionnaires, an additional 10% is added, resulting in a final sample size of approximately 422 respondents. A total of 422 questionnaires were administered; however, only 312 questionnaires were duly completed and returned, representing a 73.9% response rate. This number was considered adequate for statistical analysis and valid generalization within the scope of the study. In social science and field-based studies involving mobile populations and geographically dispersed respondents, moderate response rates are common due to literacy barriers, respondent mobility, and suspicion of authorities, time constraints, and logistical challenges.

Table 1: Sampling frame and questionnaire allocation by communities

S/N	Host Community/staff	Estimated Population	Available Sample	Percentage (%)
1.	Port managers	Indeterminate	**15**	**4.8**
2.	Marine engineers	Indeterminate	**22**	**7.1**
3.	Maritime safety officers	Indeterminate	**37**	**11.9**
4.	Terminal operators	Indeterminate	**48**	**15.4**
5.	Shipping company personnel	Indeterminate	**67**	**21.5**
6.	Port planners	Indeterminate	**08**	**2.6**
7.	Logistics and supply chain managers	Indeterminate	**63**	**20.2**
8.	Maritime regulatory officials	Indeterminate	**52**	**16.6**
Total			**312**	**100%**

Source: Field Survey, 2026

2.5 Methods of data collection

Data for this study were collected through survey method using researchers' developed structured questionnaire titled "Spatial Adequacy Benchmark and Sustainable Maritime Operations Questionnaire (SABSMOQ)." The structured questionnaire was designed in sections to elicit responses on the roles, perceptions, and experiences of the respondents regarding the impact of spatial adequacy benchmark on sustainable maritime operations (SMO).

2.6 Methods of data analysis

Data generated using the SABSMOQ was analyzed using descriptive statistics such as frequency, mean and standard deviation to provide answers to the research questions, while the hypothesis was tested using Pearson Product Moment Correlation (PPMC) at 0.05 level of significance. These methods are considered appropriate for measuring the strength and direction of the relationship between variables.

3. Results and interpretations

3.1 Respondents' experience in spatial adequacy benchmark

The experience of respondents in spatial adequacy benchmark was analyzed interms workspace, movement during operations storage and frequency of constraint. These indicators are presented in the following tables;

Table 1. Analysis of respondents' experience of spatial adequacy and maritime operations

Tick the extent of your agreement to the adequacy of workspace in your operations interms of;	**Very adequate f (%)**	**Adequate f (%)**	**Inadequate f (%)**	**Very inadequate f (%)**	**Mean ($\bar{X}$)**	**Std. Dev**
Working convenience	32 (10.3)	38 (12.2)	131 (42)	111 (35.6)	3.03	0.94
Movement during operations	51 (16.3)	54 (17.3)	115 (36.9)	92 (29.5)	2.79	1.04
Storage space	41 (13.1)	49 (15.7)	141 (45.2)	81 (26.0)	2.84	0.96

Source: Field report, 2026.

The findings in table 1 indicate that respondents generally perceived the available workspace as adequate for operational activities. Specifically, the mean score of 3.03 (SD = 0.94) for working convenience suggests that the workspace provides a relatively comfortable and conducive environment for carrying out tasks. Similarly, the mean score of 2.79 (SD = 1.04) for movement during operations indicates that respondents considered the available space reasonably sufficient for operational mobility, although the higher standard deviation reflects greater variability in opinions. Furthermore, the mean score of 2.84 (SD = 0.96) **for** storage space implies that the existing storage facilities are moderately adequate for accommodating operational materials and equipment. Overall, since all the mean values exceed the criterion mean of 2.50, the findings suggest that the workspace is generally adequate in terms of working convenience, operational movement, and storage capacity, albeit with some variations in respondents' perceptions.

Table 2. Analysis of respondents' experience on spatial adequacy and frequency of constraint in maritime operations

Spatial adequacy	**Never f (%)**	**1-3 times f (%)**	**4-6 times f (%)**	**7 times and above f (%)**	**Mean ($\bar{X}$)**	**Std. Dev**
In the last month, how often did cramp space delay cargo handling/berthing?	25 (8.01)	42 (13.5)	109 (35.0)	136 (43.6)	3.14	0.93

Source: Field report, 2026.

The findings indicate that inadequate or cramped space constitutes a frequent constraint to maritime operations, particularly in cargo handling activities. Specifically, only 8.01% of the respondents reported that cramped space had never caused delays in cargo handling, while 13.5% indicated that such delays occurred 1–3 times. Furthermore, 35.0% of the respondents stated that cramped space delayed cargo handling 4–6 times**,** whereas the highest proportion (43.6%) reported experiencing delays 7 times and above**.** These results suggest that space inadequacy is a persistent operational challenge, with a majority of respondents (78.6%) experiencing cargo handling delays at least four times or more. This implies that insufficient operational space significantly affects the efficiency and smooth flow of maritime activities, thereby underscoring the need for improved spatial planning and expansion of maritime facilities to enhance operational performance.

Table 3. Analysis of respondents' knowledge of NIMASA spatial adequacy benchmark

S/N	Variables	True		False		Undecided	
		F	%	F	%	F	%
1.	NIMASA minimum benchmark for warehouse aisle width is 3.5m.	71	22.8	89	28.5	152	48.7
2.	NIMASA minimum benchmark per a ton of cargo for safe stacking is $2m^2$	74	23.7	86	27.6	152	48.7
3.	ILO minimum benchmark floor area per seafarer in a cabin/living room is $7.0m^{2.}$	68	21.8	76	24.4	168	53.8

Source: Field report, 2026.

The findings suggest that respondents possess a relatively low level of knowledge regarding spatial adequacy benchmarks prescribed by the Nigerian Maritime Administration and Safety Agency (NIMASA) and the International Labour Organization (ILO). Specifically, only 22.8% of the respondents correctly identified the NIMASA benchmark for warehouse aisle width of 3.5 m, while 28.5% considered it false and the majority (48.7%) remained undecided. Similarly, with respect to the benchmark of 2 m^2 per ton of cargo for safe stacking, only 23.7% indicated it as true, 27.6% regarded it as false, and 48.7% were undecided. Furthermore, concerning the ILO minimum floor area per seafarer in a cabin, only 21.8% of respondents correctly identified the benchmark, whereas 24.4% considered it false and more than half (53.8%) were undecided.

Overall, the high proportion of undecided responses across all three benchmark areas indicates considerable uncertainty and inadequate awareness among respondents regarding established spatial adequacy standards. This finding implies that knowledge of regulatory and international benchmarks is generally poor, suggesting the need for increased sensitization, training, and dissemination of spatial adequacy standards among maritime stakeholders to promote compliance and enhance operational efficiency and safety.

3.2 Research question one

Table 4: Mean and standard deviation analysis of spatial adequacy benchmarks currently utilized in maritime operations (N = 312)

S/N	Items	Mean ($\bar{X}$)	SD	Decision
1	Berth length and berth occupancy rate are utilized as benchmarks for assessing spatial adequacy in maritime operations.	3.48	0.72	Agree
2	Navigational channel width and depth serve as important spatial adequacy benchmarks in maritime operations.	3.56	0.65	Agree
3	Terminal storage yard capacity is utilized as a benchmark for evaluating spatial sufficiency in ports.	3.39	0.78	Agree
4	Vessel maneuvering and turning basin spaces are used as benchmarks for maritime spatial adequacy assessment.	3.44	0.70	Agree

S/N	Items	Mean (X̄)	SD	Decision
5	Intermodal access corridors and logistics support spaces are utilized as spatial adequacy benchmarks in maritime operations.	3.27	0.81	Agree
Grand Mean		**3.43**	**0.73**	**Agree**

The results presented in Table 4 reveal that all the identified spatial adequacy benchmarks recorded mean scores above the criterion mean of 2.50, indicating agreement among respondents that they are currently utilized in maritime operations. The highest-rated benchmark was navigational channel width and depth (X̄ = 3.56, SD = 0.65), followed by berth length and berth occupancy rate (X̄ = 3.48, SD = 0.72). Respondents also agreed that vessel maneuvering and turning basin spaces (X̄ = 3.44, SD = 0.70), terminal storage yard capacity (X̄ = 3.39, SD = 0.78), and intermodal access corridors and logistics support spaces (X̄ = 3.27, SD = 0.81) are important benchmarks used in assessing spatial adequacy in maritime operations. The grand mean of 3.43 indicates a high level of agreement among respondents regarding the utilization of these benchmarks in maritime operations.

Based on the findings, the spatial adequacy benchmarks currently utilized in maritime operations include berth length and occupancy rate, navigational channel width and depth, terminal storage yard capacity, vessel maneuvering and turning basin spaces, and intermodal access corridors with logistics support spaces. These benchmarks are widely applied in assessing the adequacy of maritime infrastructure and ensuring efficient and sustainable maritime operations.

3.3 Research question two

Table 5: Mean and standard deviation analysis on the extent to which existing maritime spatial facilities and infrastructure satisfy operational requirements (N = 312)

S/N	Items	Mean (X̄)	SD	Decision
1	Existing berthing facilities adequately accommodate vessel traffic and operational demands.	3.18	0.83	Agree
2	Navigational channels and waterways provide sufficient space for safe and efficient vessel movement.	3.26	0.79	Agree
3	Terminal storage and cargo handling areas adequately support current cargo throughput requirements.	3.11	0.87	Agree
4	Available operational spaces facilitate efficient coordination of maritime logistics and intermodal transport activities.	3.07	0.91	Agree
5	Existing maritime infrastructure possesses adequate capacity to meet present operational requirements without significant congestion.	2.96	0.95	Agree
Grand Mean		**3.12**	**0.87**	**Agree**

The results in Table 5 indicate that respondents generally agreed that existing maritime spatial facilities and infrastructure satisfy operational requirements. All five items recorded mean scores above the criterion mean of 2.50, ranging from 2.96 to 3.26. Specifically, respondents agreed that navigational channels and waterways provide sufficient space for safe and efficient vessel movement (X̄ = 3.26, SD = 0.79), making it the highest-rated item. This was followed by adequacy of berthing facilities in accommodating vessel traffic and operational demands (X̄ = 3.18, SD = 0.83). Respondents also acknowledged that terminal storage and cargo handling areas support current cargo throughput requirements (X̄ = 3.11, SD = 0.87), while operational spaces facilitate logistics and intermodal transport activities (X̄ = 3.07, SD = 0.91). The lowest mean score was recorded for the item assessing whether existing maritime infrastructure has sufficient capacity to meet operational requirements without significant congestion (X̄ = 2.96, SD = 0.95). Although respondents agreed with the statement, the relatively lower mean suggests concerns regarding congestion and capacity limitations in some maritime facilities. The grand mean of 3.12 indicates that existing maritime spatial facilities and infrastructure satisfy operational requirements to a moderate to high extent.

Based on the findings, existing maritime spatial facilities and infrastructure satisfy operational requirements to a considerable extent. Berthing facilities, navigational channels, storage areas, logistics spaces, and supporting infrastructure generally provide adequate capacity for maritime operations. However, concerns regarding congestion and infrastructure capacity constraints suggest the need for continuous improvement and expansion to sustain future operational demands and enhance maritime efficiency.

3.4 Research question three

Table 6: Mean and standard deviation analysis on the effect of spatial adequacy on environmental sustainability in maritime operations (N = 312)

S/N	Items	Mean (X̄)	SD	Decision
1	Adequate spatial planning reduces environmental congestion and operational inefficiencies within maritime facilities.	3.41	0.74	Agree
2	Availability of sufficient operational space enhances effective waste management and pollution control in maritime operations.	3.36	0.79	Agree
3	Adequate spatial infrastructure facilitates compliance with environmental protection regulations and standards.	3.28	0.82	Agree
4	Proper allocation of navigational and operational spaces minimizes environmental risks associated with vessel movement and cargo handling.	3.47	0.71	Agree
5	Spatial adequacy contributes significantly to the long-term environmental sustainability of maritime operations.	3.52	0.68	Agree
Grand Mean		**3.41**	**0.75**	**Agree**

The results presented in Table 6 reveal that respondents agreed that spatial adequacy has a positive effect on environmental sustainability in maritime operations. All the items recorded mean scores above the criterion mean of 2.50, ranging from 3.28 to 3.52. The highest mean score was obtained for the statement that spatial adequacy contributes significantly to the long-term environmental sustainability of maritime operations (X̄ = 3.52, SD = 0.68). This was closely followed by the view that proper allocation of navigational and operational spaces minimizes environmental risks associated with vessel movement and cargo handling (X̄ = 3.47, SD = 0.71).

Respondents also agreed that adequate spatial planning reduces environmental congestion and operational inefficiencies (X̄ = 3.41, SD = 0.74), while availability of sufficient operational space enhances waste management and pollution control measures (X̄ = 3.36, SD = 0.79). Furthermore, respondents acknowledged that adequate spatial infrastructure facilitates compliance with environmental regulations and standards (X̄ = 3.28, SD = 0.82). The grand mean of 3.41 indicates strong agreement among respondents that spatial adequacy exerts a substantial positive influence on environmental sustainability in maritime operations.

Based on the findings, spatial adequacy has a significant positive effect on environmental sustainability in maritime operations. Adequate spatial planning and infrastructure contribute to reduced congestion, improved waste management, enhanced compliance with environmental regulations, minimized environmental risks, and greater long-term sustainability of maritime activities. Therefore, achieving and maintaining spatial adequacy is essential for promoting environmentally sustainable maritime operations.

3.5 Research question four

Table 7: Mean and Standard Deviation Analysis of Challenges Hindering the Attainment of Spatial Adequacy in Maritime Operations in Nigeria (N = 312)

S/N	Items	Mean ($\bar{X}$)	SD	Decision
1	Inadequate investment in port infrastructure expansion limits the availability of adequate operational space in Nigerian ports.	3.58	0.67	Agree
2	Increasing cargo throughput and vessel traffic have outpaced the spatial capacity of many Nigerian maritime facilities.	3.49	0.73	Agree
3	Poor implementation of maritime spatial planning policies contributes to inadequate utilization and development of port spaces.	3.44	0.79	Agree
4	Encroachment, limited waterfront land availability, and urbanization restrict opportunities for maritime infrastructure expansion.	3.37	0.84	Agree
5	Bureaucratic delays and regulatory inefficiencies hinder timely development and optimization of maritime operational spaces.	3.53	0.71	Agree
Grand Mean		**3.48**	**0.75**	**Agree**

The results presented in Table 7 indicate that respondents agreed that several challenges hinder the attainment of spatial adequacy in maritime operations in Nigeria. All the items recorded mean scores above the criterion mean of 2.50, with values ranging from 3.37 to 3.58. The findings reveal that the most significant challenge is inadequate investment in port infrastructure expansion ($\bar{X}$ = 3.58, SD = 0.67), indicating that insufficient financial commitment to maritime infrastructure development constrains the availability of adequate operational space. Respondents also agreed that bureaucratic delays and regulatory inefficiencies ($\bar{X}$ = 3.53, SD = 0.71) and increasing cargo throughput and vessel traffic exceeding available spatial capacity ($\bar{X}$ = 3.49, SD = 0.73) constitute major impediments to achieving spatial adequacy. Furthermore, respondents identified poor implementation of maritime spatial planning policies ($\bar{X}$ = 3.44, SD = 0.79) as a significant factor contributing to spatial inadequacies. Similarly, encroachment, limited waterfront land availability, and urbanization pressures ($\bar{X}$ = 3.37, SD = 0.84) were recognized as constraints on the expansion of maritime infrastructure and facilities. The grand mean of 3.48 indicates a high level of agreement among respondents that these challenges significantly hinder the attainment of spatial adequacy in Nigeria's maritime sector.

Based on the findings, the attainment of spatial adequacy in maritime operations in Nigeria is hindered by inadequate investment in port infrastructure expansion, increasing cargo and vessel traffic, poor implementation of maritime spatial planning policies, limited waterfront land availability and urbanization pressures, as well as bureaucratic and regulatory inefficiencies. The grand mean score of 3.48 suggests that these challenges substantially impede the development and maintenance of adequate maritime operational spaces required for efficient, safe, and sustainable maritime operations in Nigeria.

3.6 Research question five

Table 8: Mean and standard deviation analysis of measures for improving spatial adequacy benchmarks for sustainable maritime operations in Nigeria (N = 312)

S/N	Items	Mean ($\bar{X}$)	SD	Decision
1	Increased investment in port infrastructure expansion and modernization should be adopted to improve spatial adequacy.	3.71	0.58	Agree
2	Periodic review and enforcement of maritime spatial planning policies and benchmarks should be strengthened.	3.63	0.66	Agree
3	Adoption of advanced technologies for port planning, space optimization, and traffic management should be encouraged.	3.54	0.72	Agree
4	Development of additional deep-sea ports, logistics hubs, and intermodal transport facilities should be prioritized.	3.68	0.61	Agree
5	Public-private partnerships should be promoted to facilitate sustainable financing and expansion of maritime infrastructure.	3.59	0.69	Agree
Grand Mean		**3.63**	**0.65**	**Agree**

The results presented in Table 4.6 reveal that respondents agreed on all the proposed measures for improving spatial adequacy benchmarks for sustainable maritime operations in Nigeria. All the items recorded mean scores above the criterion mean of 2.50, ranging from 3.54 to 3.71. The highest-rated measure was increased investment in port infrastructure expansion and modernization ($\bar{X}$ = 3.71, SD = 0.58), indicating that respondents consider infrastructure development essential for achieving spatial adequacy. This was closely followed by development of additional deep-sea ports, logistics hubs, and intermodal transport facilities ($\bar{X}$ = 3.68, SD = 0.61). Respondents also agreed that periodic review and enforcement of maritime spatial planning policies and benchmarks ($\bar{X}$ = 3.63, SD = 0.66) would enhance compliance with spatial adequacy requirements. Similarly, public-private partnerships for sustainable infrastructure financing ($\bar{X}$ = 3.59, SD = 0.69) and adoption of advanced technologies for port planning, space optimization, and traffic management ($\bar{X}$ = 3.54, SD = 0.72) were identified as important measures for improving spatial adequacy in the maritime sector. The grand mean of 3.63 indicates a very high level of agreement among respondents that these measures would significantly improve spatial adequacy benchmarks and promote sustainable maritime operations in Nigeria.

Based on the findings, the key measures that can be adopted to improve spatial adequacy benchmarks for sustainable maritime operations in Nigeria include increased investment in port infrastructure expansion and modernization, regular review and enforcement of maritime spatial planning policies, adoption of advanced technologies for space optimization and traffic management, development of additional deep-sea ports and logistics hubs, and promotion of public-private partnerships for infrastructure financing. The grand mean score of 3.63 indicates that these measures are widely regarded by respondents as effective strategies for enhancing spatial adequacy and ensuring sustainable maritime operations in Nigeria.

4. Discussion of findings

4.1 Spatial adequacy benchmarks currently utilized in maritime operations

The findings revealed that the major spatial adequacy benchmarks currently utilized in maritime operations include berth length and occupancy rate, navigational channel width and depth, terminal storage yard capacity, vessel maneuvering spaces, and intermodal access corridors. The high grand mean score ($\bar{X}$ = 3.43) indicates that respondents widely recognize these benchmarks as critical indicators for assessing the adequacy of maritime infrastructure and operational spaces.

This finding aligns with the work of Theofanis, Boile, and Golias (2009), who identified berth capacity, navigational accessibility, and terminal space utilization as fundamental benchmarks for evaluating port performance and operational effectiveness. Similarly, Pereira, Netto, Botter, and Medina (2017) observed that adequate berth dimensions, storage facilities, and maneuvering areas are essential criteria used in modern port planning and capacity assessment. The finding is further supported by Zanin, Silva, and Gomes (2020), who reported that port spatial adequacy is commonly measured through infrastructure capacity indicators such as storage space, channel dimensions, and logistics connectivity. The result suggests that maritime operators in Nigeria and elsewhere rely on established spatial benchmarks to ensure efficient vessel movement, cargo handling, and sustainable maritime operations.

4.2 Existing maritime spatial facilities and infrastructure for sustainable operations

The findings showed that existing maritime spatial facilities and infrastructure satisfy operational requirements to a considerable extent, as evidenced by the grand mean score of 3.12. Respondents agreed that berthing facilities, navigational channels, storage yards, and logistics spaces generally provide adequate support for vessel movement, cargo handling, and maritime logistics operations. This suggests that available maritime infrastructure contributes positively to operational effectiveness, although concerns about congestion and capacity limitations remain.

The finding corroborates the study of Chang, Tongzon, Luo, and Lee (2012), who found that adequate port infrastructure and spatial capacity are critical determinants of operational efficiency and service quality in maritime transport systems. Similarly, Pereira et al. (2017) reported that sufficient berthing spaces, storage facilities, and navigational infrastructure enhance cargo throughput and reduce operational bottlenecks in ports. The result is also consistent with Zanin et al. (2020), who observed that ports with adequate spatial infrastructure demonstrate better operational performance and greater capacity to accommodate growing maritime traffic. However, the relatively lower rating on congestion-free operations supports the assertion of Vesel, O'Connor, and O'Shaughnessy (2023) that increasing trade volumes often place pressure on existing port capacities, necessitating continuous infrastructure expansion and modernization.

4.3 Spatial adequacy and environmental sustainability in maritime operations

The findings revealed that spatial adequacy has a significant positive effect on environmental sustainability in maritime operations, as indicated by the high grand mean score of 3.41. Respondents agreed that adequate spatial planning promotes effective waste management, reduces operational congestion, minimizes environmental risks, and enhances compliance with environmental regulations. This implies that sufficient allocation and utilization of maritime spaces contribute substantially to achieving sustainable environmental outcomes in maritime operations.

This finding is consistent with the study of Lam and Notteboom (2014), who observed that efficient port spatial planning enhances environmental performance by reducing congestion, emissions, and operational inefficiencies within port environments. Similarly, Puig, Wooldridge, Michail, and Darbra (2015) found that adequate port infrastructure and spatial organization facilitate environmental management practices, including pollution control and waste handling systems. The result also supports the findings of Moussa et al. (2026), who reported that sustainable maritime infrastructure planning is essential for environmental protection, resource optimization, and long-term sustainability in maritime operations. Furthermore, Ceylan et al. (2026) emphasized that spatial adequacy provides the foundation for implementing green port initiatives and achieving sustainable maritime development goals.

4.4 Challenges of spatial adequacy in maritime operations

The findings revealed that the attainment of spatial adequacy in maritime operations in Nigeria is hindered by inadequate infrastructure investment, increasing cargo and vessel traffic, poor implementation of maritime spatial planning policies, land constraints, and regulatory inefficiencies. The grand mean score of 3.48 indicates that respondents strongly perceive these factors as major impediments to achieving adequate maritime operational space and sustainable port development.

This finding is consistent with the study of Notteboom and Rodrigue (2005), who observed that rapid growth in maritime trade often outpaces port infrastructure development, resulting in congestion and spatial inadequacies. Similarly, UNCTAD (2023) reported that insufficient investment in port infrastructure and poor policy implementation remain significant challenges affecting port efficiency and capacity utilization in many developing countries. The finding also supports the work of Onwuegbuchunam, Ekwenna, and Igboanugo (2017), who identified inadequate funding, bureaucratic bottlenecks, and poor infrastructure expansion as major constraints to port development in Nigeria. Furthermore, Akinwale and Aremo (2021) noted that urban encroachment and limited waterfront land availability significantly restrict port expansion and the attainment of optimal spatial standards in Nigerian seaports.

4.5 Measures to improve spatial adequacy benchmarks for sustainable maritime operations

The findings revealed that improving spatial adequacy benchmarks for sustainable maritime operations in Nigeria requires increased investment in port infrastructure, regular review and enforcement of spatial planning policies, adoption of advanced technologies, development of additional deep-sea ports and logistics hubs, and promotion of public-private partnerships. The high grand mean score of 3.63 indicates a strong consensus among respondents that these measures are critical for enhancing maritime spatial capacity and sustainability.

This finding is consistent with the position of UNCTAD (2023), which emphasized that continuous investment in port infrastructure and modernization is essential for improving port capacity, operational efficiency, and sustainability. Similarly, Notteboom, Pallis, and Rodrigue (2021) argued that strategic port expansion, technological innovation, and integrated logistics systems are indispensable for addressing spatial constraints and enhancing port competitiveness. The finding also aligns with the study of Lam and Notteboom (2014), who found that effective maritime spatial planning and the adoption of smart port technologies significantly improve resource utilization and environmental performance. Furthermore, the work of World Bank (2020) highlighted public-private partnerships as an effective mechanism for mobilizing financial resources required for large-scale maritime infrastructure development in emerging economies.

5. Conclusions

Based on the findings of this study, the following conclusions were drawn:

1. Spatial adequacy benchmarks such as berth length and occupancy rates, navigational channel dimensions, terminal storage capacity, vessel maneuvering spaces, and intermodal logistics corridors are widely utilized in maritime operations and serve as critical indicators for evaluating maritime infrastructure performance.
2. Existing maritime spatial facilities and infrastructure generally satisfy operational requirements to a considerable extent. However, increasing maritime traffic and cargo volumes are exerting pressure on available capacities, creating concerns regarding congestion and future operational sustainability.
3. Spatial adequacy exerts a significant positive influence on environmental sustainability in maritime operations. Adequate spatial planning enhances waste management, minimizes environmental risks, reduces operational congestion, and promotes compliance with environmental regulations.
4. The attainment of spatial adequacy in Nigerian maritime operations is constrained by inadequate infrastructure investment, poor implementation of maritime spatial planning policies, increasing cargo and vessel traffic, regulatory inefficiencies, and limitations in available land for expansion.
5. Sustainable maritime operations in Nigeria can be enhanced through increased infrastructure investment, effective policy implementation, adoption of advanced technologies, expansion of port facilities, and strengthened public-private sector collaboration.

Overall, the study concludes that spatial adequacy remains a fundamental prerequisite for achieving operational efficiency, environmental sustainability, and safety in maritime operations, while inadequate spatial provision poses a significant threat to the long-term sustainability of Nigeria's maritime sector.

5.1 Recommendations

Based on the findings and conclusions of the study, the following recommendations are made:

1. Government and private sector stakeholders should increase investments in port infrastructure expansion, modernization, and maintenance to ensure adequate spatial capacity for current and future maritime operations.

2. Relevant maritime authorities should develop and enforce comprehensive spatial planning policies and benchmarks that align with international best practices and sustainable development objectives.

3. Additional deep-sea ports, logistics hubs, cargo terminals, and intermodal transport facilities should be developed to accommodate increasing cargo volumes and vessel traffic while reducing congestion in existing ports.

4. Port operators should deploy digital technologies, Geographic Information Systems (GIS), artificial intelligence, automated traffic management systems, and real-time monitoring tools to optimize the utilization of available maritime spaces.

5. Port authorities should ensure strict compliance with established spatial adequacy standards relating to navigational channels, berth spacing, turning basins, and cargo handling areas to improve maritime safety performance.

These recommendations, if effectively implemented, will enhance spatial adequacy, improve operational efficiency and safety, strengthen environmental sustainability, and promote the long-term competitiveness of Nigeria's maritime industry.

5.2 Implications of the Study

The findings of this study on the have significant implications for policy, practice, theory, and future research.

1. The study underscores the necessity for policymakers to formulate and enforce comprehensive maritime spatial planning policies that incorporate internationally recognized spatial adequacy benchmarks. The findings suggest that inadequate spatial infrastructure can undermine operational efficiency, safety, and environmental sustainability. Consequently, government agencies and maritime regulators must prioritize long-term infrastructure planning, periodic capacity assessments, and effective implementation of maritime development policies to ensure sustainable maritime growth.

2. The study highlights the need for continuous expansion and modernization of maritime infrastructure. Port authorities and infrastructure developers must recognize that existing facilities may become inadequate as cargo volumes and vessel traffic increase. Therefore, infrastructure investments should be guided by established spatial adequacy benchmarks to ensure that ports remain capable of meeting current and future operational demands.

3. The findings demonstrate that spatial adequacy directly influences operational efficiency within maritime facilities. This implies that maritime operators should adopt proactive space management strategies, optimize terminal layouts, improve cargo handling systems, and integrate advanced technologies to maximize the utilization of available operational spaces. Improved spatial adequacy is likely to reduce congestion, enhance cargo throughput, and improve overall service delivery.

4. The established relationship between spatial adequacy and maritime safety performance suggests that adherence to spatial adequacy benchmarks is essential for reducing navigational risks, operational accidents, and safety incidents. Maritime administrators should therefore ensure strict compliance with standards relating to berth allocation, channel dimensions, turning basins, and cargo handling areas to enhance safety performance across maritime facilities.

5. Improved spatial adequacy has the potential to enhance port productivity, reduce vessel waiting times, minimize operational costs, and increase cargo handling efficiency. Consequently, achieving spatial adequacy can strengthen the competitiveness of Nigerian ports, attract greater maritime investments, facilitate trade, and contribute positively to national economic growth and regional trade integration.

The overarching implication of this study is that spatial adequacy is not merely an infrastructure requirement but a strategic determinant of sustainable maritime operations**.** Any deficiency in maritime spatial planning and infrastructure provision can adversely affect operational efficiency, safety performance, environmental sustainability, and economic competitiveness. Therefore, achieving and maintaining spatial adequacy should be regarded as a critical priority for sustainable maritime development in Nigeria and other maritime economies.

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