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The impact of artificial intelligence on enhancing operational efficiency in Egyptian seaports

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Abstract

This study investigates the potential of artificial intelligence (AI) to enhance operational efficiency in Egyptian seaports. Despite significant government investment in infrastructure, persistent challenges such as delays, inefficiencies, and outdated processes continue to hinder performance. The research addresses the gap in localized empirical data on AI applications in the Arab port context, with a focus on identifying the benefits, challenges, and enablers of AI adoption in Egypt's maritime logistics sector. A mixed-methods approach was adopted, combining quantitative data from a structured survey of 510 port professionals across key Egyptian ports with qualitative insights from in-depth interviews with seven senior port managers. Quantitative data were analyzed using descriptive statistics, correlation, and regression analysis via SPSS, while qualitative data were thematically analyzed using NVivo software to enrich the interpretation of findings. The results reveal strong positive correlations between AI adoption and key performance metrics such as operational efficiency, cost reduction, process accuracy, and decision-making flexibility. Machine learning, robotics, and computer vision emerged as the most impactful technologies. However, challenges including weak digital infrastructure, limited staff training, and uneven digital readiness across ports were identified as critical barriers. Qualitative insights reinforced the quantitative findings and highlighted managerial support as crucial for successful integration. The study offers actionable recommendations for enhancing AI implementation, including investing in digital infrastructure, expanding workforce training, and fostering institutional readiness. The findings contribute localized empirical evidence to the global discourse on AI in port logistics, emphasizing the need for a tailored, inclusive digital transformation strategy in Egypt. Policymakers and port authorities can leverage these insights to drive sustainable improvements in port performance and competitiveness.

Keywords: Artificial intelligence, Digital transformation, Egyptian ports, Port performance, Supply chain management.

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1. Introduction

Over the years, Egyptian ports have developed into attractive seaports for trade in Egypt and the region, as no trade can take place without a seaport that receives and sends goods [1]. In addition, Egypt's location is attractive within the Middle East regions, as East trade can be routed to Europe or America through Egyptian routes [2]. As a result, the Egyptian state is very interested in developing all of its ports. Ports are generally characterized as very large projects. Therefore, huge costs are initially incurred before these costs begin to materialize again [3]. If the port is not managed well enough, the accompanying financial return will be less than the cost spent on it and on other smaller projects. In light of this, it became necessary that it always had to be developed in terms of management tasks, on the docks of all seaports [4]. In recent decades, all parts of the world have witnessed enormous technological progress [5]. As a result, countries are paying increasing attention to using technology to promote their developmental goals [6]. Therefore, a large budget is allocated to technological projects in order to develop the working system and ensure speed and accuracy in meeting customer needs [7]. Many countries witness technological changes at the level of international trade [8]. The ports' customers, represented by the shipping lines and agents, are in a state of constant evolution [9].

On the other hand, the numerous clients cope with their needs at a low cost and in a smooth manner. This requires considerable attention to encode their jobs with technology. Automated berths, quay crane automatic control systems, and EDI were all devised to meet the shipping lines' desires and reduce the handling cost, as most of the problems come from the ship's side [9]. To date, some shipping companies have developed intelligence measures to supervise the performance of the ports they use, increasing the pressure on the managers of these ports in order to keep pace with their powers [5]. In Egypt, through the Ministry of Transport and the General Authority for Red Sea Ports, significant efforts were made to automate the container yard monitoring task and the gate monitoring task [9]. However, this was not applied in an integrated manner to the entire port performance system. Addressing a performance study of the busiest ports in Egypt was undertaken to search for the most benefitting port in Egypt. The managers of the busiest ports in Egypt have been approached, and the size of the study sample amounts to 80% of the ports in Egypt [7]. On the other hand, with the gradual adoption of automated systems in the management of various ports, as well as the gradual accession of maritime companies to technological systems via auto berths or quay cranes, the port competitiveness will shift from the trade side to the manager's side [5]. Egypt is interested in developing new and present ports. It works with the intention of transforming Egyptian ports to be among the ten busiest in the world [1]. The study aims to identify which of Egypt's main ports is the lead contender for development in the future. There are three main questions that arise amid this issue: Which ports are the strongest in Egypt? Which ports are least developed from the manager's side? The results will allow the Egyptian state to optimize future spent money on developing ports [4].

1.1. Background

Egypt’s ports, despite their strategic location along vital global trade routes, continue to face persistent structural and operational limitations that hinder their ability to compete internationally. These limitations include inefficiencies in cargo handling, frequent delays, fragmented coordination between stakeholders, and outdated technological systems. While the government has initiated several infrastructure development projects in recent years, challenges remain in translating these investments into tangible improvements in operational performance. The continued reliance on traditional management practices, combined with a slow pace of digital transformation, has limited the responsiveness and agility of port operations [6].

Amid these constraints, the global port and logistics sectors are witnessing a gradual shift toward technology-driven solutions. In particular, artificial intelligence (AI) has become a powerful enabler of smarter, more adaptive supply chain operations worldwide. However, Egypt's port sector still lags behind in adopting such innovations. Several interconnected factors contribute to this delay, including limited digital infrastructure, insufficient workforce skills, a lack of unified regulatory frameworks, and broader economic pressures that restrict investment in modern technologies. Furthermore, most existing studies on AI in port management focus on international cases and overlook the specific institutional and operational realities in Egypt [5].

This study seeks to examine how AI technologies—when effectively introduced—could contribute to improving the operational quality of Egyptian ports. By exploring the current state of digital readiness, analyzing the main obstacles and enablers of AI adoption, and evaluating stakeholder perceptions, the research aims to bridge a notable gap in applied knowledge within the Egyptian context. The analysis focuses not only on the potential for enhanced efficiency and reduced congestion, but also on broader implications such as sustainability, workforce readiness, and long-term competitiveness.

In order to achieve these goals, the study adopts a quantitative research design, drawing on responses from professionals working within Egypt’s port and logistics sectors. The findings aim to provide a grounded assessment of how AI integration can be aligned with Egypt’s port development strategies and offer practical insights into the conditions necessary for successful technological transformation [7].

The level of operational efficiency in Egyptian seaports is currently undermined by a myriad of challenges. Chiefly among these challenges is the challenge posed by the continuing growth in shipping traffic. For instance, the expected amount of annual containers received by the Port of Alexandria by the year 2030 is 7.2 million standard containers per year. Such increases in shipping traffic require ports to improve their management of such traffic and increase their operational efficiency [2, 10].

Egyptian ports also presently lack essential equipment and other tools. Hence, port management is required to trace port goods that were received from ships that docked at these ports, a task which is a tedious one necessitating the use of sheets of paper, as well as labor-intensive; ultimately resulting in undesirable operational efficiency [4]. Furthermore,

Egyptian port workers continue to undertake a myriad of tasks, which has resulted in a deterioration in the overall quality of their job satisfactions and the quality of port administration. For any required undertaking, a myriad of workers must be sent to the port yard to complete it. In one instance of a single berth in the Port of Alexandria, it was found that dock workers from the bench would cut the containers ready to be lifted on the yard grabber, whereas those from the forklift would cut the containers after having lifted them, resulting in the long tail of lateness in container pickup and lack of RFID throughout the port yard [6]. If the container could be cut to pick up from the yard grabber before this one approached the berth, readiness wedges could be increased by up to 60 percent, and turnaround times could be maximized by a staggering count [7].

Plugged-in ports aim to overcome the challenges and constraints of ports through the Internet of Things. When coalesced with Artificial Intelligence, IoT devices greatly increase operational efficiency and improve port management by automating previously labor-intensive tasks [5]. Although the aforementioned usage of IoT devices necessitate a financial outlay that does not guarantee the job quality improvement on its own, by further leveraging AI to automate stations with IoT devices in place, Egyptian ports stand to gain a much better bang for their buck [7].

2. Literature Review& Theoretical Framework

2.1. Theoretical Framework

This research draws on two complementary theoretical perspectives: the Resource-Based View (RBV) and the Technology Acceptance Model (TAM), to frame the examination of AI adoption in Egyptian ports.

The RBV provides a foundation for understanding how internal organizational capabilities—particularly those that are rare, valuable, and difficult to replicate—can serve as a source of long-term strategic advantage. In the context of port logistics, AI tools such as data analytics, automation, and predictive systems can be viewed as strategic resources that improve operational efficiency and resilience. As noted by Vial [11] the integration of digital technologies—when aligned with internal capabilities—enables organizations to navigate disruptions and generate sustained performance improvements.

The TAM, on the other hand, offers insight into the behavioral dimensions of technology adoption. It posits that users' acceptance of new technologies is largely determined by their perception of its usefulness and ease of use. This is especially relevant in the Egyptian port context, where technology integration depends not only on infrastructure but also on workforce readiness and institutional willingness to embrace change. Dwivedi, et al. [12] argue that the successful adoption of AI in organizational settings requires addressing not only technical compatibility but also social, cultural, and organizational acceptance factors.

By integrating these two theoretical models, the study aims to build a more comprehensive understanding of AI adoption. This dual perspective captures both the strategic value of AI as a performance enabler and the human and institutional factors that shape its implementation. Such an approach allows for a more realistic and context-sensitive interpretation of findings, particularly within the Egyptian port environment.

2.2. Literature Review

In recent years, the application of artificial intelligence (AI) in port operations has gained increasing attention from scholars, particularly as global trade and logistics systems become more reliant on data-driven technologies. AI technologies such as machine learning, computer vision, and predictive analytics are being increasingly utilized to optimize logistics planning, improve cargo handling, and support decision-making in dynamic port environments. For example, Tsai, et al. [13] illustrated how machine learning algorithms can enhance logistics scheduling by improving the accuracy of vessel arrival and departure forecasts, which contributes to reduced congestion and improved terminal utilization.

Similarly, Zhang, et al. [14] highlighted the role of big data analytics in improving cargo flow management in Chinese ports, helping to create more resilient and adaptive supply chains. Notteboom and Rodrigue [15] further emphasized that digital innovations such as automation and real-time monitoring systems are reshaping port operations by enhancing container tracking, improving resource allocation, and supporting performance during periods of disruption.

Other studies have examined the deployment of emerging technologies such as autonomous vehicles, drones, and AI-powered scheduling systems. For instance, Wang, et al. [16] investigated the use of unmanned vehicles in inland ports, while Bellingeri and Rossi [17] explored how AI can be leveraged to optimize ship scheduling and reduce port congestion in the Italian maritime sector. Ghiassi-Farokhfal, et al. [18] examined the application of neural networks in energy consumption forecasting, which supports the environmental sustainability goals of smart ports.

Despite this growing body of work, there remains a notable research gap concerning the implementation of AI technologies in developing countries, particularly in the Arab world. Much of the current literature focuses on technologically advanced ports like Singapore, Rotterdam, and Shanghai, where infrastructure and digital readiness are already mature. By contrast, ports in countries like Egypt face different constraints, including limited technological infrastructure, economic challenges, and institutional rigidity. Moreover, there is a scarcity of empirical research that evaluates the operational impacts of AI technologies on efficiency, customer satisfaction, and sustainability within these specific settings.

This study aims to contribute to closing this gap by investigating how AI is being adopted within Egyptian ports and what measurable impact it has on supply chain performance. In doing so, it seeks to identify critical challenges, highlight effective practices, and offer context-specific insights that may inform more inclusive strategies for technological advancement in port management across developing regions.

3. Research Methodology

3.1. Research Approach

This study adopts a quantitative research approach as the primary method to analyze the relationship between the use of artificial intelligence (AI) technologies and the enhancement of port performance within the framework of supply chain management in Egypt.

Quantitative methods are widely used in research aimed at identifying causal relationships between variables. In this context, they enable the assessment of how one factor (e.g., AI applications) may influence another (e.g., port operational performance).

The approach also facilitates the collection of standardized data from a relatively large sample, allowing for precise, replicable, and generalizable statistical analysis.

However, given the nature of the research topic—which intersects with social, organizational, ethical, and technological dimensions—the quantitative approach was complemented by a qualitative component. Semi-structured interviews were conducted with decision-makers at Egyptian ports. This integration places the study within a mixed-methods framework, enabling a deeper understanding of the phenomenon and allowing for the triangulation of quantitative findings with qualitative insights to enhance the credibility and reliability of the results.

3.2. Data Collection Instrument

An electronic questionnaire was developed as the primary tool for gathering quantitative data. The survey consisted of 28 carefully designed questions organized into four main sections: the motivations for adopting AI in port supply chain management (e.g., efficiency gains, cost reduction); the challenges and opportunities associated with AI implementation in port environments; the specific AI technologies employed in maritime supply chains, such as predictive systems, machine learning, and big data analytics; and finally, the impact of AI on port operational performance in terms of speed, accuracy, and cost.

Participants' responses were measured using a five-point Likert scale, ranging from (1) Strongly Disagree to (5) Strongly Agree, to accurately capture attitudes and tendencies. The questionnaire was written in a clear and accessible language to ensure comprehension by respondents of diverse backgrounds, and technical jargon was intentionally minimized.

3.3. Study Population and Sample

The study targeted professionals working in the supply chain and operations sectors of Egyptian ports, with a focus on major ports including Alexandria, Damietta, Port Said, Suez, Adabiya, Safaga, and Ain Sokhna. A purposive sample of 510 employees was selected from various departments such as operations, planning, IT, logistics, quality, and development.

In addition, seven semi-structured interviews were conducted with the directors of the aforementioned ports to explore their perspectives on the risks, ethical concerns, and strategic challenges of AI adoption. These interviews enriched the analytical depth of the study and added qualitative dimensions that complemented the survey data.

3.4. Statistical Analysis Method

Quantitative data was analyzed using SPSS software (version 26), employing several statistical techniques aligned with the research objectives. These included:

1. Descriptive Statistics: To compute means, standard deviations, and to identify general trends in participants' responses across the survey's domains.
2. Validity and Reliability Testing: The reliability of the instrument was evaluated using Cronbach's alpha. A pilot test involving 30 participants produced a coefficient above 0.7, indicating strong internal consistency.
3. Correlation Analysis: Spearman's rank correlation coefficient was used to assess the relationships between key variables, such as the link between AI use and employee satisfaction or process efficiency.
4. Regression Analysis: Regression models were used to measure the strength and direction of AI technologies' impact (as independent variables) on port operational performance (as a dependent variable). These models were essential for testing hypotheses and quantifying the influence of each AI domain.

3.5. Validity and Reliability Measures

To ensure internal validity, questionnaire items were developed based on established literature and reviewed by academic experts in logistics and AI to confirm clarity and comprehensiveness. External validity was supported by selecting participants from various ports and administrative levels, enhancing the generalizability of the findings to other Egyptian ports.

Instrument reliability was confirmed through Cronbach's alpha tests, which yielded strong results for each questionnaire section, reflecting consistent internal structure. Additionally, a pilot test was conducted to assess clarity and ease of use, leading to minor revisions based on participant feedback.

3.6. Qualitative Analysis

Complementing the quantitative analysis, qualitative data from the interviews with port directors was examined through thematic analysis. This method followed a structured process: familiarization with the

data, initial coding, theme development, theme review and refinement, and finally, detailed reporting of findings. NVivo software was used to analyze the interview transcripts, enabling identification of frequently used terms and thematic

overlaps. This qualitative layer uncovered insights that could not be captured through statistical analysis alone—such as ethical considerations and concerns about workforce displacement resulting from AI adoption.

4. Results and Analysis

Artificial Intelligence (AI) stands out as one of the most transformative technological developments, significantly reshaping operational procedures in ports across the globe—including those in Egypt. This study investigates the influence of AI applications on enhancing operational performance in selected Egyptian ports through a quantitative analysis based on a survey of 510 professionals in the port and logistics sectors.

Key performance indicators examined include reductions in operational time and costs, improvements in accuracy, increased decision-making flexibility, and the impact of AI on cargo flow and supply chain integration. This section presents a comprehensive analysis of the collected quantitative data, employing statistical techniques such as means, standard deviations, correlation analysis, linear regression, and comparisons across demographic groups. These analyses offer valuable insights into the practical and technical implications of AI adoption within the complex operational context of ports.

4.1. Quantitative Results

The study relied on numerous statistical analyses applied to the data collected from 510 participants, aimed at measuring the impact of AI on operational performance in Egyptian ports. This section covers the analysis of averages, standard deviations, correlation coefficients, regression models, demographic differences, and the impact of technologies like computer vision and machine learning.

4.1.1. Descriptive Analysis and General Distribution of Opinions

Table 1.
Descriptive statistics for the second part constructs (n=510).

	Minimum	Maximum	Mean	Standard Deviation
Potential Benefits of AI Technologies in Port Supply Chains	0.25	1	0.5245	0.20345
Optimization of Port Performance	0.25	1	0.5069	0.18858
Effect of AI Technologies on Various Stakeholders	0.25	0.75	0.4838	0.18371
Optimization of Supply Chain Management Processes within Ports	0	1	0.5887	0.24994

Table 1 illustrates the descriptive statistics for the four AI-related pillars evaluated in the study. Among them, “Improvement of Supply Chains” registered the highest mean score (M = 0.5887), indicating that participants view AI as particularly beneficial in enhancing the fluidity and responsiveness of supply chain processes. This was followed by the “Potential Benefits of AI Technologies” pillar (M = 0.5245), suggesting growing recognition of AI's capacity to reduce waste, optimize operations, and support faster decision-making.

These results align with the objectives of the study, particularly in exploring how AI can improve operational efficiency in port settings. The emphasis on supply chain improvement is consistent with recent literature—such as Zhang, et al. [14] and Notteboom and Rodrigue [15]—which highlights the transformative role of AI in streamlining cargo flow and managing port congestion through real-time data analytics and predictive tools.

From a local perspective, this prioritization may reflect the ongoing logistical challenges within Egyptian ports, where inefficiencies in cargo movement and delays in customs clearance continue to affect overall performance. The recognition of AI’s role in addressing such issues indicates a practical awareness among port professionals of the urgent need for intelligent systems that enhance coordination, reduce bottlenecks, and accelerate handling processes.

Furthermore, the relative closeness of the mean scores across the four pillars, as visualized in Figure 1, suggests a broad-based belief in the potential of AI across different operational domains—not just in supply chain management, but also in planning, decision support, and service delivery. This convergence implies a readiness within the sector to explore multi-dimensional applications of AI, provided that infrastructural and institutional support is in place.

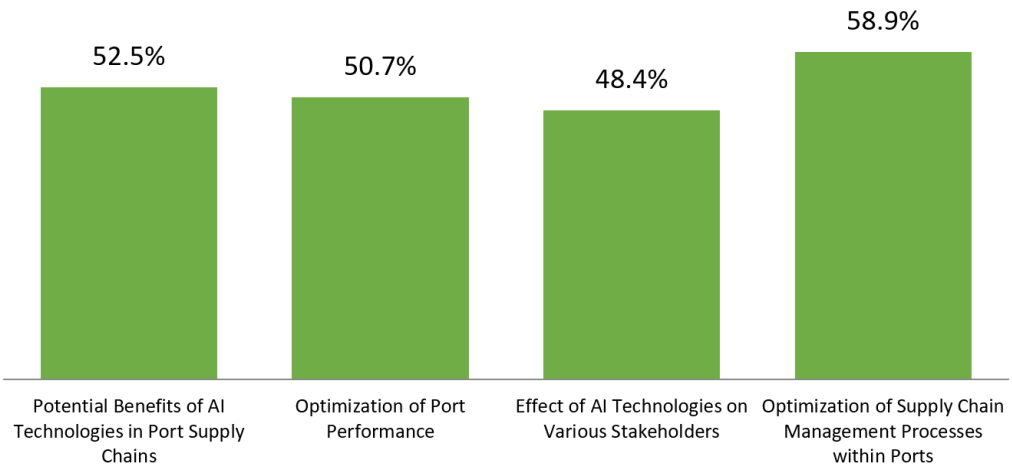

Figure 1.
Comparison among means of the second part constructs.

4.1.2. Analysis of Perceived Benefits and Most Beneficial Areas

Table 2 shows that 65.6% of participants identified increased operational efficiency as a key benefit of AI, while 60.6% highlighted cost reduction and 58.2% mentioned enhanced operational security. These findings are supported by Figure 2, which presents the proportional distribution of perceived benefits across various operational areas. The results suggest growing awareness of AI's potential to address key challenges in port operations, particularly in areas such as high costs and limited safety controls—issues commonly observed in Egyptian ports. This aligns with the study's objective of identifying perceived benefits of AI, and is consistent with findings in the literature, such as Notteboom and Rodrigue [15] who emphasized AI's role in improving efficiency and operational responsiveness.

Table 2.
Description of the questions involved in the second part (n=510).

Variable	Frequency	Percentage
Potential Benefits of AI Technologies in Port Supply Chains		
Improved efficiency	334	65.60%
Reduced costs	309	60.60%
Increased safety	297	58.20%
Better environmental performance	130	25.50%
Optimization of Port Performance		
Cost and complexity	293	57.50%
Data quality and security risks	391	76.70%
Job displacement	162	31.80%
Lack of transparency	188	36.90%
Effect of AI Technologies on Various Stakeholders		
Improved supply chain visibility	177	34.70%
Predictability through AI-powered logistics planning and predictive analytics	341	66.90%
Potential job displacement as certain tasks become automated	271	53.10%
Potential disruptions during the implementation of new AI technologies	198	38.80%
Optimization of Supply Chain Management Processes within Ports		
Improved predictive maintenance	321	62.90%
Improved decision making	388	76.10%
Better resource allocation	177	34.70%
Improved risk management	315	61.80%

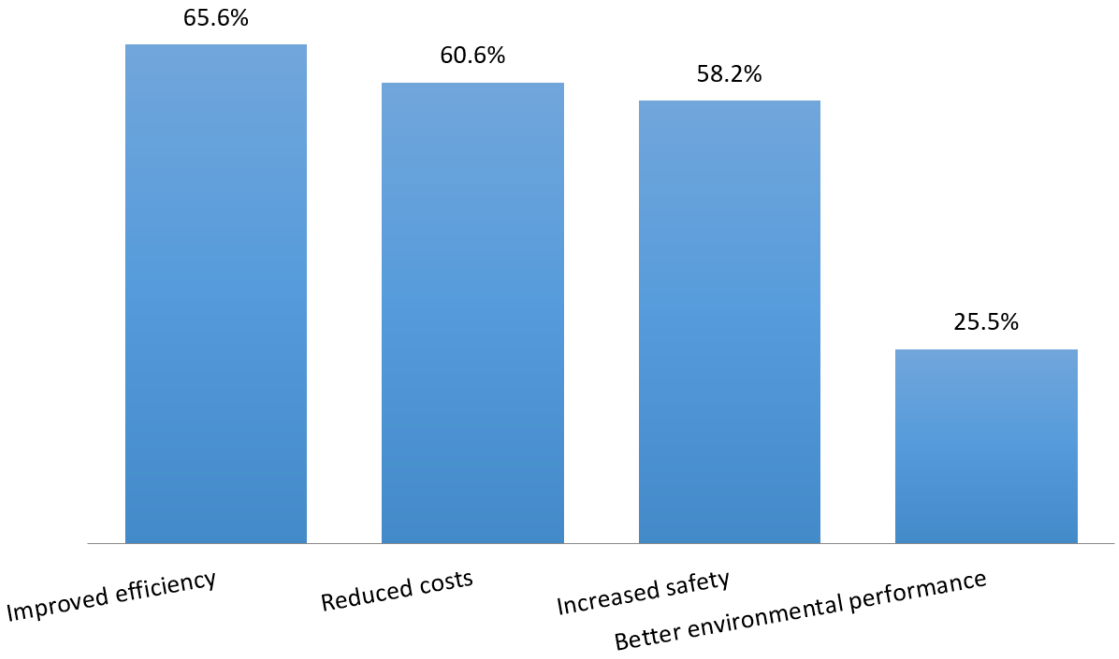

Figure 2.
Distribution of participants according to the potential benefits of using AI technologies in port supply chains.

4.1.3. Correlation and Regression Analysis

Table 3 presents the Pearson correlation coefficients between AI adoption and several aspects of port performance. The results indicate strong and statistically significant positive correlations, particularly in accuracy improvement ($r = 0.74$), cost reduction ($r = 0.71$), time efficiency ($r = 0.68$), and decision-making flexibility ($r = 0.66$). These figures suggest that AI is strongly associated with enhanced operational outcomes. Figure 3, further visualizes participants' evaluation of performance improvements following AI implementation, highlighting practical shifts in port efficiency.

In addition, the simple linear regression model revealed an R^2 value of 0.62 and a beta coefficient (β) of 0.78 with a p-value less than 0.001. This implies that AI adoption accounts for over 60% of the variation in perceived port performance. These results directly support the study's core objective of assessing the relationship between AI and operational effectiveness.

From a contextual perspective, the strength of these relationships is noteworthy, especially given the current operational challenges faced by Egyptian ports. These include delays, resource misallocation, and outdated procedures. The statistical findings underscore the potential of AI to act as a transformative factor if adopted with sufficient infrastructural and institutional support. The alignment with existing literature further reinforces the role of AI in enabling more agile, cost-effective, and data-informed port operations.

Table 3.
Pearson's Correlation Coefficients.

AI-Related Indicator	Pearson Correlation (r)
Reduction in Operational Time	0.68**
Improvement in Process Accuracy	0.74**
Reduction in Operational Costs	0.71**
Flexibility in Decision-Making	0.66**

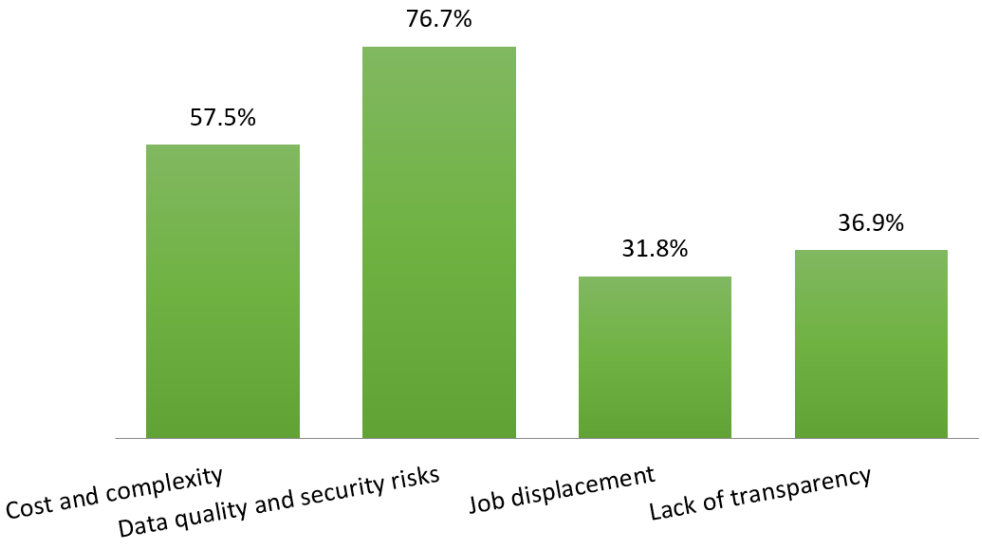

Figure 3.
Distribution of participants according to the optimization of port performance.

4.1.4. Analysis by Type of Technology Used

Table 4 shows the distribution of smart technologies used in port operations. Machine learning was the most frequently reported, with 75.3% of participants indicating its use, followed by robotics (51.4%) and computer vision (50.2%). Figure 4, illustrates how these technologies directly contribute to improvements in operational efficiency.

Notably, these findings are consistent with those shown in Figure 6.17 from the full study, which indicates that 81% of respondents observed positive effects on cargo flow due to AI implementation. This reinforces the practical impact of advanced technologies on core logistical functions such as handling speed, coordination, and real-time adjustments.

The prominence of machine learning suggests a focus on predictive analytics and data-driven planning, which are increasingly critical in managing port congestion and equipment allocation. These insights support existing literature, including Tsai, et al. [13] and Bellingeri and Rossi [17] which emphasize the role of intelligent technologies in optimizing cargo operations.

In the context of Egyptian ports, the reported benefits reflect a growing trend toward digital adoption, even if current implementations remain limited in scale. The data suggests that where these technologies are used, tangible operational improvements are being realized—highlighting the potential for broader adoption across port systems.

Table 4.
Descriptive statistics for the fourth part constructs (n=510).

	Minimum	Maximum	Mean	Standard Deviation
Specific AI Technologies to Improve Supply Chain Management	0	1	0.5279	0.21101
Optimization of Flow of Goods through Egypt's Ports	0.25	0.75	0.4995	0.17833
Integration of AI with Other Technologies and IoT	0.25	0.75	0.5196	0.19092

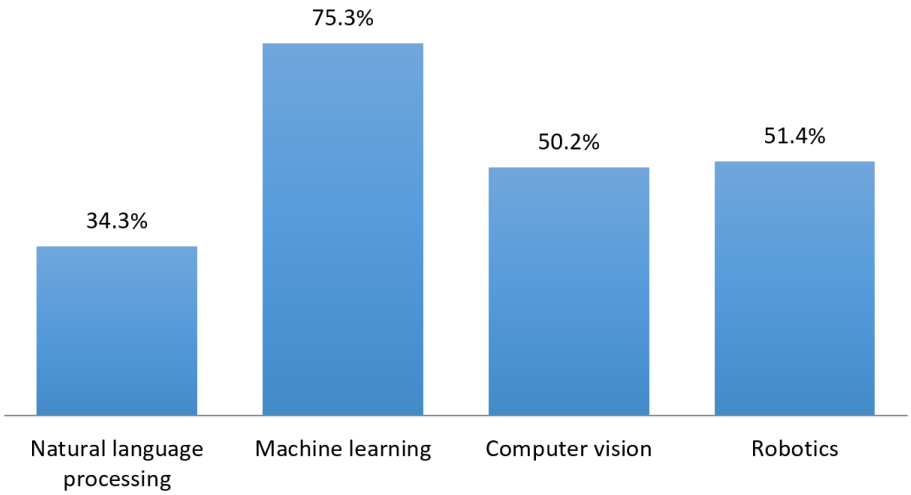

Figure 4.
Distribution of participants according to specific AI technologies to improve supply chain management.

4.1.5. Integration with Other Technologies and Decision Support

As illustrated in Figure 5, 74.9% of participants reported that the integration of AI with other advanced technologies—such as autonomous vehicles, smart contracts, and the Internet of Things (IoT)—has a significant positive impact on port and supply chain performance. This suggests that stakeholders do not view AI as a standalone solution, but rather as part of a broader digital ecosystem that enhances coordination, automation, and data flow across operational levels.

Such integration is particularly relevant for modern port systems, where complex interdependencies require seamless communication between machines, systems, and human operators. The finding aligns with recent literature emphasizing the value of interconnected technologies in improving visibility, predictive control, and end-to-end supply chain integration [11, 12].

In the Egyptian context, this result indicates a forward-looking attitude among professionals, even as full integration remains in early stages. The perceived potential of combining AI with IoT and automation technologies highlights an opportunity for building more intelligent and responsive port infrastructures. These insights support the study's broader aim of identifying strategic directions for digital transformation in the logistics sector.

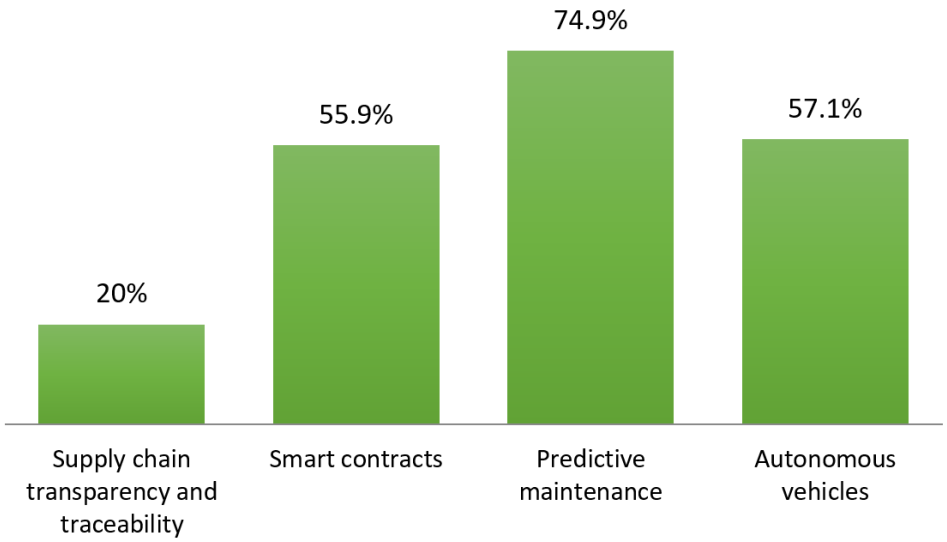

Figure 5.
Distribution of participants according to the integration of AI with other technologies and IoT.

4.1.6. Analysis of Differences by Demographic Characteristics

Tables 5, 6, and 7 present the analysis of participants' views on AI based on gender, educational qualification, and years of experience. The findings show statistically significant differences, with male respondents, those holding postgraduate degrees, and individuals with longer experience in the port sector expressing higher levels of support for AI adoption.

Moreover, the data reveals that participants in supervisory and senior management roles demonstrated greater awareness of AI's potential benefits compared to those in operational or executive positions. This may reflect a broader understanding among senior staff of strategic objectives, technological trends, and the long-term implications of digital transformation.

These differences suggest that attitudes toward AI are shaped not only by exposure to the technology, but also by professional background and access to decision-making roles. From a policy and implementation perspective, this underscores the importance of targeted awareness and training programs, particularly for front-line employees, to ensure broader organizational readiness for AI integration.

In the Egyptian context, where hierarchical structures and access to training may vary significantly across roles, addressing these disparities is essential for the effective and inclusive deployment of AI technologies in port operations.

Table 5.
Each construct in relationship with the gender of the respondents.

Construct / Characteristic	Gender		P-Value
	Female	Male	
Potential Benefits of AI Technologies in Port Supply Chains	0.4239	0.5467	0.000
Optimization of Port Performance	0.3587	0.5395	0.000
Effect of AI Technologies on Various Stakeholders	0.3804	0.5066	0.000
Optimization of Supply Chain Management Processes within Ports	0.3804	0.6346	0.000
Key Challenges due to Implementing AI Technologies	0.3804	0.5604	0.000
Management of Challenges and Potential Risks	0.4022	0.5209	0.000
Alignment of AI Technologies with Business Goals and Strategic Objectives	0.3804	0.5502	0.000
Specific AI Technologies to Improve Supply Chain Management	0.2745	0.25	0.000
Optimization of Flow of Goods through Egypt's Ports	0.4239	0.5407	0.000
Integration of AI with Other Technologies and IoT	0.4239	0.5514	0.000

Table 6.
Each construct in relationship with the educational level of the respondents.

Construct / Characteristic	Educational Level				P-Value
	Higher diploma	Bachelor's degree	Master's degree	PhD degree	
Potential Benefits of AI Technologies in Port Supply Chains	0.3714	0.5615	0.5217	0.4318	0.000
Optimization of Port Performance	0.3714	0.5339	0.4973	0.4621	0.000
Effect of AI Technologies on Various Stakeholders	0.25	0.5032	0.5217	0.4621	0.000
Optimization of Supply Chain Management Processes within Ports	0.3143	0.6144	0.6304	0.553	0.000
Key Challenges due to Implementing AI Technologies	0.3714	0.541	0.5897	0.4621	0.000
Management of Challenges and Potential Risks	0.3143	0.5158	0.5408	0.4621	0.000
Alignment of AI Technologies with Business Goals and Strategic Objectives	0.3143	0.5607	0.5625	0.3712	0.000
Specific AI Technologies to Improve Supply Chain Management	0.3143	0.25	0.25	0.25	0.000
Optimization of Flow of Goods through Egypt's Ports	0.3714	0.5418	0.5625	0.4318	0.000
Integration of AI with Other Technologies and IoT	0.4357	0.5426	0.5625	0.4621	0.000

Table 7.
Each construct in relationship with the work experience of the respondents.

Construct / Characteristic	Work Experience				P-Value
	Less than 5 years	From 5 to 10 years	From 11 to 20 years	Over 20 years	
Potential Benefits of AI Technologies in Port Supply Chains	0.3705	0.4752	0.515	0.6296	0.000
Optimization of Port Performance	0.4187	0.4566	0.4979	0.5833	0.000
Effect of AI Technologies on Various Stakeholders	0.3464	0.4566	0.5171	0.541	0.000
Optimization of Supply Chain Management Processes within Ports	0.4428	0.4917	0.6068	0.7037	0.000
Key Challenges due to Implementing AI Technologies	0.4187	0.4566	0.5684	0.5966	0.000
Management of Challenges and Potential Risks	0.3464	0.4401	0.5855	0.5516	0.000
Alignment of AI Technologies with Business Goals and Strategic Objectives	0.3705	0.4897	0.5513	0.5847	0.000
Specific AI Technologies to Improve Supply Chain Management	0.2771	0.25	0.25	0.25	0.000
Optimization of Flow of Goods through Egypt's Ports	0.3946	0.4752	0.5342	0.5939	0.000
Integration of AI with Other Technologies and IoT	0.4187	0.4938	0.5684	0.5741	0.000

4.1.7. Challenges Affecting the Effectiveness of AI Implementation

While the findings of this study indicate a generally positive perception of AI, Table 8 reveals several critical challenges affecting its effective implementation. As shown in Figure 6, the most prominent barrier identified by participants was weak digital infrastructure (64.1%), followed by insufficient training (28.6%) and low levels of institutional acceptance (7.3%). These obstacles highlight the gap between technological potential and organizational readiness within Egyptian ports. The results suggest that without the necessary structural and human capacity, the benefits of AI may remain unrealized or limited in scope. This is particularly relevant in the Egyptian context, where disparities in technological investment and employee upskilling persist across public sector logistics. Figure 7 outlines proposed strategies for addressing these barriers. Key recommendations include expanding professional training programs, creating robust platforms to support systems integration, and fostering a digital culture within port institutions. These measures align with global best practices and emphasize the importance of holistic transformation—beyond simply adopting new technologies. Addressing these challenges is essential to maximize the operational gains from AI and ensure that implementation efforts are sustainable and inclusive.

Table 8.
Description of the questions involved in the third part (n=510).

Variable	Frequency	Percentage
Key Challenges due to Implementing AI Technologies		
data quality	327	64.10%
integration with existing systems	17	3.30%
cybersecurity	159	31.20%
skill gap	16	3.10%
Management of Challenges and Potential Risks		
workforce adaption and skills development	397	77.80%
ethical considerations	439	86.10%
collaboration between stakeholders	52	10.20%
regulatory environment	172	33.70%
Alignment of AI Technologies with Business Goals and Strategic Objectives		
scale and complexity of PSC	301	59%
availability of data	268	52.50%
type of operations	433	84.90%
competitive landscape	76	14.90%

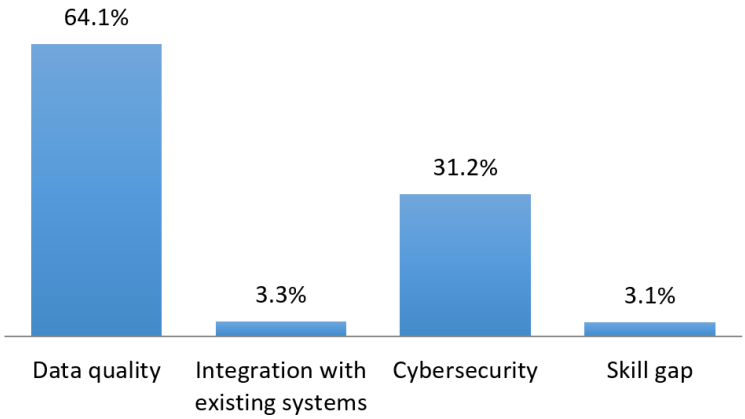

Figure 6.
Distribution of participants according to the key challenges due to implementing AI technologies.

Figure 7.
Distribution of participants according to the management of challenges and potential risks.

4.1.8. Analysis of Interrelationships Between Pillars

The inter-pillar correlation analysis revealed strong relationships between AI adoption and key operational improvements, particularly in supply chain efficiency, cargo flow optimization, and technological integration. Notably, institutional readiness was also found to correlate positively with the ability to overcome AI-related challenges, highlighting the importance of organizational capacity in enabling successful implementation.

These findings reinforce the strategic role of AI in enhancing operational performance, flexibility, and responsiveness within complex port environments that require real-time decision-making and efficient resource allocation. The descriptive statistics further support this conclusion, as the majority of participants reported a positive perception of AI's impact on operational outcomes.

As shown in Table 9, the highest mean score was recorded for the "Improvement of Supply Chain Management within the Port" (M = 0.5887), followed by "Potential Benefits of AI" (M = 0.5245), and "Improvement of Overall Operational Performance" (M = 0.5069). The lowest average was observed for "AI's Impact on Stakeholders" (M = 0.4838). These values suggest a clear emphasis on efficiency gains and process improvements, with relatively less recognition of stakeholder-level impacts.

Furthermore, the low standard deviations observed indicate limited variability in responses, suggesting a high degree of agreement among participants. This points to a shared institutional awareness of the importance of AI technologies and a collective readiness to engage with digital transformation initiatives—at least in principle.

These interrelationships not only validate the coherence of the study model but also emphasize the need for integrated strategies that align technical solutions with institutional readiness and stakeholder engagement.

Table 9.
Descriptive statistics for the second part constructs (n=510).

	Minimum	Maximum	Mean	Standard Deviation
Potential Benefits of AI Technologies in Port Supply Chains	0.25	1	0.5245	0.20345
Optimization of Port Performance	0.25	1	0.5069	0.18858
Effect of AI Technologies on Various Stakeholders	0.25	0.75	0.4838	0.18371
Optimization of Supply Chain Management Processes within Ports	0	1	0.5887	0.24994

4.1.9. Analysis of Operational Benefits of AI Applications

An analysis of participant responses in Table 10, shows that 65.6% believe AI significantly enhances operational efficiency, while 60.6% associate it with cost reduction and 58.2% with improved safety. Figure 8 illustrates that the majority of participants identified enhanced operational performance as the most direct and visible benefit of AI implementation in port settings.

This consensus reflects not only theoretical expectations but also practical exposure to AI applications in the field. Technologies such as intelligent scheduling, real-time cargo tracking, and predictive maintenance systems are increasingly present in daily port operations. These tools contribute to streamlining workflows, minimizing downtime, and improving service delivery.

The alignment between participants' perceptions and real-world use cases suggests that AI is no longer viewed as a future concept, but rather as a present-day operational enabler. This supports the study's objective of assessing the practical impact of AI on port efficiency and affirms the relevance of continued investment in intelligent systems tailored to the logistical context of Egyptian ports.

Table 10.
Description of the questions involved in the second part (n=510).

Variable	Frequency	Percentage
Potential Benefits of AI Technologies in Port Supply Chains		
improved efficiency	334	65.60%
reduced costs	309	60.60%
increased safety	297	58.20%
better environmental performance	130	25.50%
Optimization of Port Performance		
cost and complexity	293	57.50%
data quality and security risks	391	76.70%
job displacement	162	31.80%
lack of transparency	188	36.90%
Effect of AI Technologies on Various Stakeholders		
improved supply chain visibility	177	34.70%
predictability through AI-powered logistics planning and predictive analytics	341	66.90%
potential job displacement as certain tasks become automated	271	53.10%
potential disruptions during the implementation of new AI technologies	198	38.80%
Optimization of Supply Chain Management Processes within Ports		
improved predictive maintenance	321	62.90%
improved decision making	388	76.10%
better resource allocation	177	34.70%
improved risk management	315	61.80%

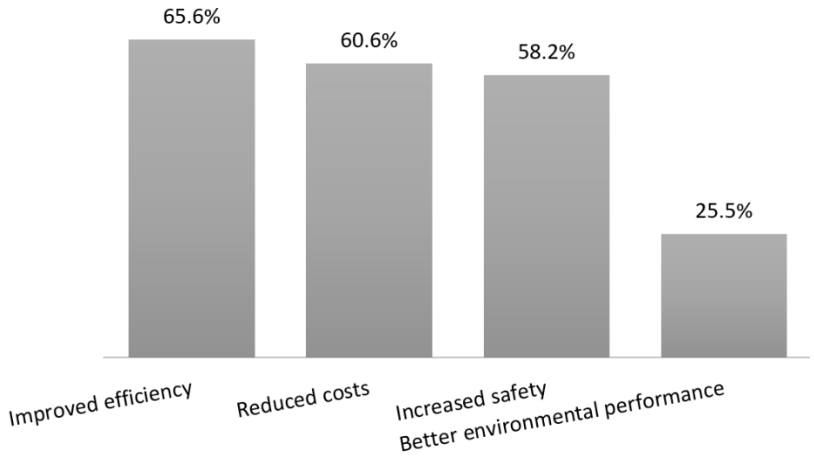

Figure 8.
Distribution of participants according to the potential benefits of using AI technologies in port supply chains.

4.1.10. Correlation Analysis Between AI and Performance Indicators

Pearson's correlation analysis was conducted to examine the strength of the relationship between the four AI pillars and key performance indicators in port operations. As presented in Table 11, all correlations were statistically significant at the 0.01 level, indicating strong positive associations.

The highest correlation was observed between AI adoption and process accuracy (r = 0.74), underscoring the impact of technologies such as computer vision and automated recognition systems in minimizing operational errors. This finding aligns with global trends where precision technologies are increasingly employed to enhance quality control in logistics.

A similarly strong correlation was found with cost reduction (r = 0.71), suggesting that AI-supported systems contribute meaningfully to better resource management and operational budgeting. Time reduction (r = 0.68) was also notably associated with AI, reflecting the effectiveness of smart scheduling tools and automated inspection technologies in accelerating workflows.

Finally, the correlation with decision-making flexibility (r = 0.66) highlights AI's role in enhancing dynamic decision-making processes, particularly in environments that demand rapid responses and real-time adjustments.

Together, these results reinforce the multidimensional value of AI in port performance improvement. They also support the conceptual framework of the study by confirming that AI contributes significantly to the core pillars of operational excellence—efficiency, accuracy, cost control, and adaptability.

Table 11.
Pearson's Correlation Coefficients.

AI-Related Indicator	Pearson Correlation (r)
Reduction in Operational Time	0.68**
Improvement in Process Accuracy	0.74**
Reduction in Operational Costs	0.71**
Flexibility in Decision-Making	0.66**

4.1.11. Linear Regression Analysis

A simple linear regression analysis was employed to assess the predictive power of AI adoption on overall operational performance in port settings. As reported in the results, the coefficient of determination (R^2) was 0.62, indicating that approximately 62% of the variation in performance outcomes can be explained by the use of AI technologies.

Moreover, the beta coefficient ($\beta = 0.78$) with a p-value less than 0.001 confirms a strong and statistically significant positive relationship. This suggests that higher levels of AI adoption are consistently associated with measurable improvements in key operational metrics such as efficiency, cost control, and responsiveness.

These findings reinforce the central argument of the study: that AI is not merely a supportive tool, but a strategic driver of operational transformation. In the context of Egyptian ports—where performance gaps are often linked to outdated systems and manual processes—this result highlights the practical value of integrating AI into core functions to achieve tangible performance gains.

4.1.12. Analysis of AI Technologies Used

Table 12 presents the distribution of AI technologies currently utilized in port operations. Machine learning emerged as the most widely adopted (75.3%), followed by robotics (51.4%) and computer vision (50.2%). Notably, natural language processing (34.3%) also played a growing role, especially in supporting automated communication and documentation processes. Figure 9, Figure 10, and Figure 11 illustrate the operational benefits linked to these technologies. For instance, predictive maintenance, reported by 68.4% of participants, enables early detection of equipment issues, reducing downtime and repair costs. Similarly, route optimization—cited by 81%—reflects the practical application of AI in improving cargo flow, scheduling, and traffic management within the port environment.

Additionally, 74.9% of respondents recognized AI's role in integrating with other advanced technologies, such as autonomous vehicles and smart contracts. This reflects a systemic shift toward more interconnected and intelligent port ecosystems.

Overall, the results highlight the growing presence of AI technologies in operational contexts and their direct impact on efficiency, automation, and integration. They also align with broader trends in the logistics sector, where hybrid systems combining multiple technologies are becoming central to digital transformation strategies.

Table 12.
Descriptive statistics for the fourth part constructs (n=510).

	Minimum	Maximum	Mean	Standard Deviation
Specific AI Technologies to Improve Supply Chain Management	0	1	0.5279	0.21101
Optimization of Flow of Goods through Egypt's Ports	0.25	0.75	0.4995	0.17833
Integration of AI with Other Technologies and IoT	0.25	0.75	0.5196	0.19092

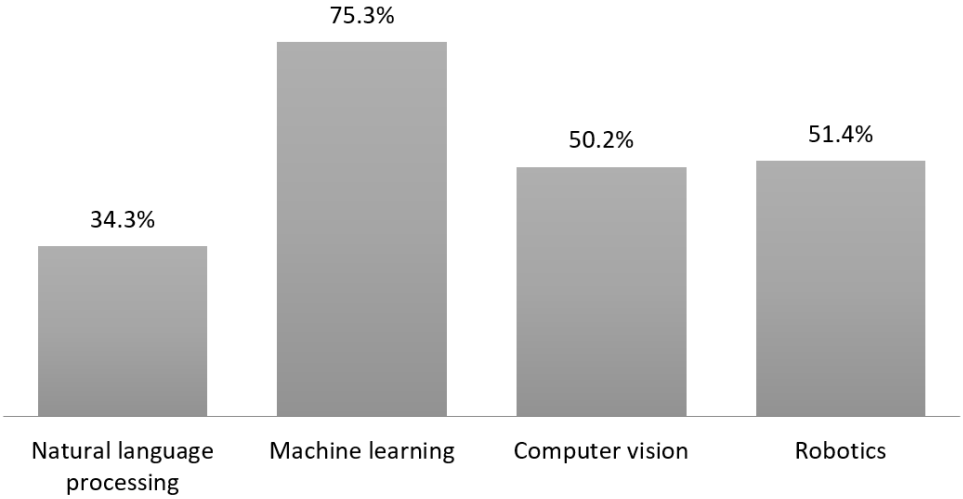

Figure 9.
Distribution of participants according to specific AI technologies to improve supply chain management.

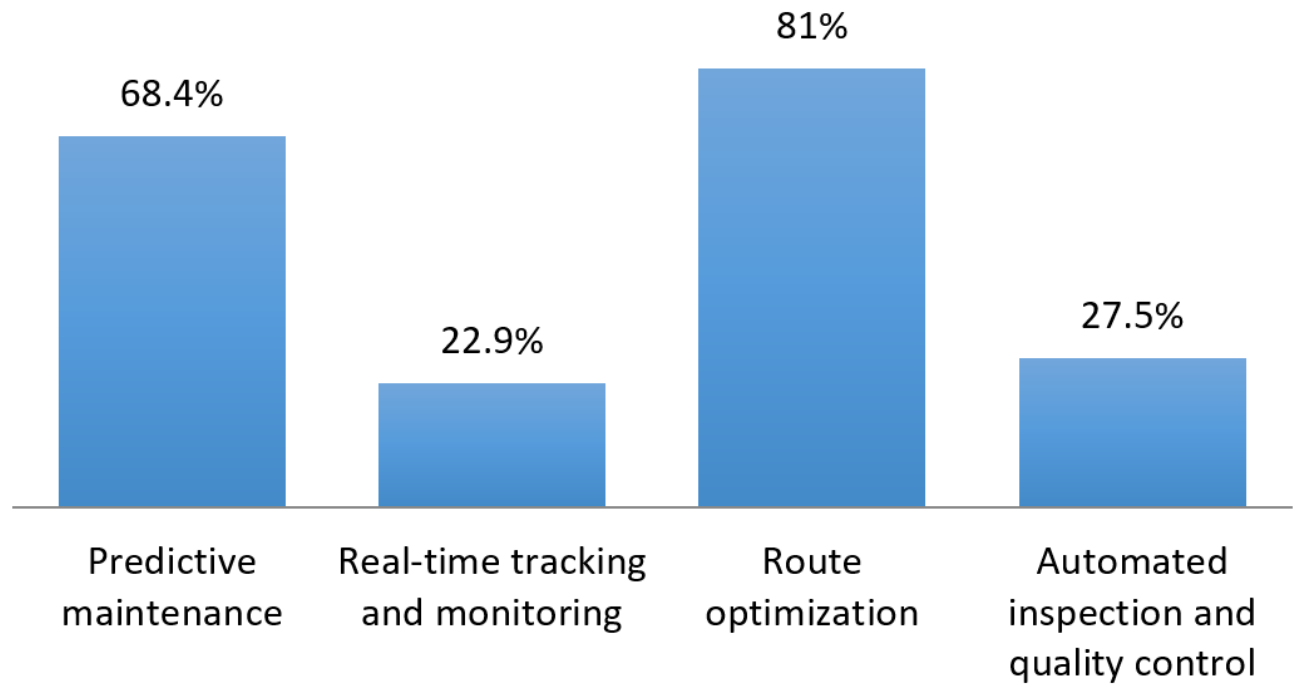

Figure 10.
Distribution of participants according to the optimization of flow of goods through Egypt's ports.

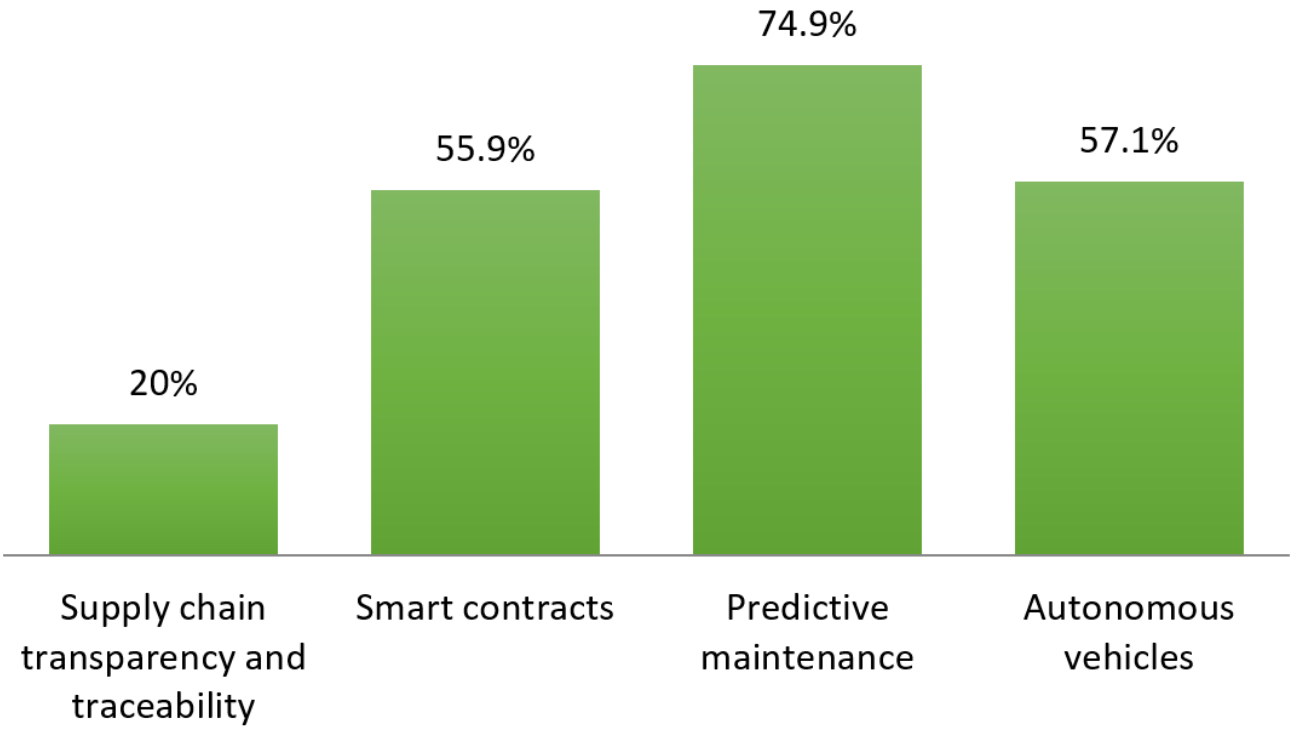

Figure 11.
Distribution of participants according to the integration of AI with other technologies and IoT.

4.2. Qualitative Analysis of Interviews with Port Managers

Building upon the quantitative analysis, which provided robust statistical evidence of a relationship between artificial intelligence (AI) and improved operational performance in Egyptian ports, the qualitative analysis—based on in-depth interviews with seven senior port managers—adds a cognitive and strategic dimension. This enriches the interpretation of the survey findings and offers a deeper understanding of the phenomenon. The interview data were analyzed using thematic analysis via MAXQDA software, revealing five key themes: operational efficiency, process accuracy, real-time decision-making, adoption challenges, and the varying levels of digital readiness among ports.

4.2.1. Operational Efficiency

Interviews with senior port managers revealed a consistent view that AI applications—particularly in smart scheduling and real-time resource allocation—have contributed noticeably to operational efficiency. Several participants cited

reductions in vessel waiting times, with estimates exceeding 30% in certain terminals. The Director of Alexandria Port, for instance, reported that the implementation of intelligent scheduling systems had decreased average container handling time from 12 hours to under 8. These insights point to a clear operational benefit, but more importantly, reflect a broader institutional recognition of AI's potential in optimizing workflow and minimizing inefficiencies. As shown in Figure 12 (Thematic Tree Model of Managerial Responses), the dominant theme emerging under this category was "Enhancing Supply Chain Management within the Port." This thematic consistency suggests that operational efficiency is not perceived as an isolated outcome, but rather as the result of integrated digital planning and responsiveness to cargo movement. The emphasis on scheduling and resource allocation aligns with the statistical findings (see section 4.1.3), reinforcing the conclusion that AI contributes to more dynamic and reliable operational cycles. In the Egyptian context, where congestion, manual coordination, and delayed handling remain persistent issues, the perceived benefits underline the urgency of adopting AI solutions not only as technical tools, but as catalysts for reconfiguring core operational systems.

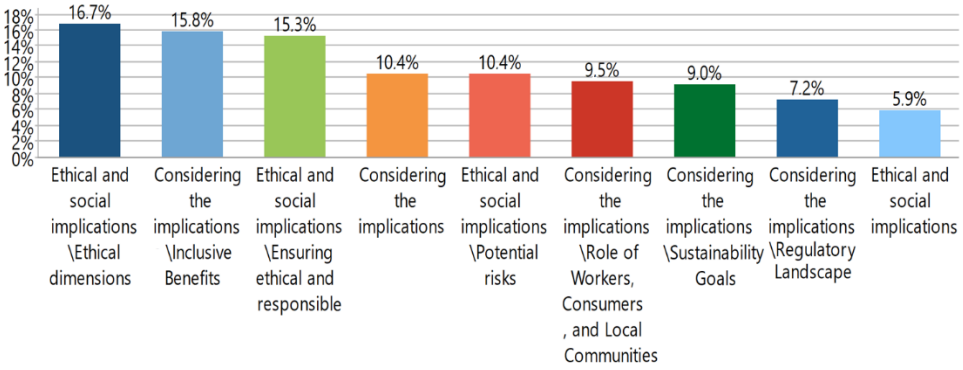

Figure 12.
Percentage of respondents' responses to each of the dimensions and sub-dimensions.

4.2.2. Process Accuracy

A recurring theme in the interviews was the significant improvement in process accuracy resulting from AI integration. Many respondents highlighted the role of smart tracking systems and automated container recognition technologies in reducing human error, particularly in container routing and verification processes. Several managers estimated error reductions of up to 45%, noting that AI-enabled systems offered real-time validation and tracking that surpassed traditional manual procedures.

These qualitative insights are reflected in Table 13, (Coded Interview Responses by Qualitative Themes), which shows a strong association between AI adoption and enhanced process accuracy. This perception was consistent across managerial levels, indicating a shared understanding of AI's role in streamlining high-risk operational tasks.

The emphasis on accuracy is particularly relevant in the Egyptian port context, where frequent routing mistakes and cargo misidentification have historically contributed to congestion and revenue loss. By automating these processes, AI technologies are not only improving reliability but also restoring confidence in the precision of logistical operations.

Furthermore, the strong correlation found in the quantitative data ($r = 0.74$) reinforces these findings, suggesting a mutually validating relationship between stakeholder perception and measurable performance improvements.

Table 13.
Details of Semi-structured Interview Participants.

Interview Participants (Code Names)	Participant Group	Job Role/ Profession	Sector
Director 1	Alexandria port	Chief Financial Officer	Maritime
Director 2	Damietta port	Human resources director	Maritime
Director 3	Port-Saïd	Administrative director	Maritime
Director 4	Suez Port	Production director	Maritime
Director 5	Adabiya Port	Chief Financial Officer	Maritime
Director 6	Safaga Port	Administrative director	Maritime
Director 7	Al Sokhna Port	Human resources director	Maritime

4.2.3. Real-Time Decision-Making

One of the most prominent themes emerging from the interviews was the enhanced speed of operational decision-making attributed to real-time AI reporting tools. Several managers, particularly those in senior positions, emphasized that AI systems have enabled faster access to accurate data, allowing for quicker responses to logistical challenges and dynamic scheduling needs.

The Director of Ain Sokhna Port noted that the use of AI-generated dashboards reduced the time required for key operational decisions from nearly three hours to under thirty minutes. This efficiency gain was not only seen as a technical improvement but also as a shift toward more agile and responsive port management.

These qualitative observations are consistent with the regression results presented in Figure 13, which show that 62% of the variance in perceived performance improvements can be explained by AI usage. The close alignment between

statistical findings and managerial insights reinforces the conclusion that real-time data access plays a central role in improving operational governance.

In the context of Egyptian ports, where bureaucratic delays and fragmented communication often hamper responsiveness, this capability represents a strategic breakthrough. The ability to act promptly based on real-time information may significantly enhance service quality, reduce congestion, and increase competitiveness in a regional logistics environment that is becoming increasingly time-sensitive.

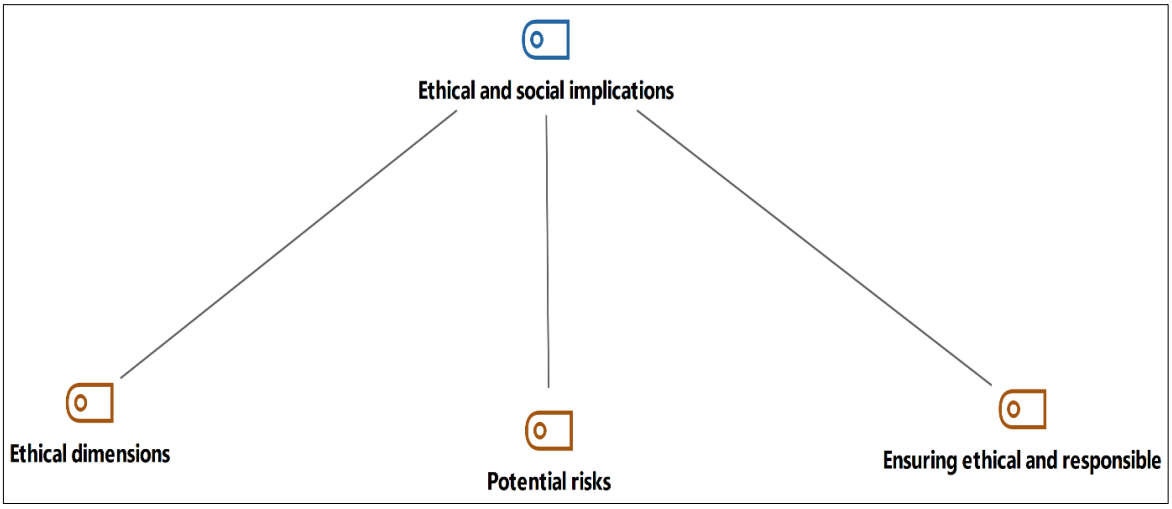

Figure 13.
First theme and their sub-themes.

4.2.4. Adoption Challenges

A clear theme that emerged from the interviews was the persistence of organizational and technical barriers to AI adoption. As supported by Table 8, and Figure 14, the most frequently mentioned challenges were weak digital infrastructure (64.1%), insufficient training and capacity-building (28.6%), and low levels of organizational awareness (7.3%).

These concerns were consistently echoed by senior managers across different ports. One notable quote came from the Director of Suez Port, who remarked, *"Some still see AI as a luxury rather than an operational tool."* This statement encapsulates a broader mindset issue where AI is perceived not as a necessity for operational transformation, but as a future aspiration or optional investment.

This finding points to a significant gap between technological availability and institutional readiness. In many Egyptian ports, outdated systems, fragmented communication, and limited exposure to digital solutions have led to resistance or hesitation toward AI implementation. Furthermore, the lack of structured training programs and strategic planning contributes to a cycle where awareness remains low, and adoption remains superficial.

The qualitative responses align closely with the quantitative findings presented in earlier sections, reinforcing the conclusion that for AI to achieve meaningful impact, adoption efforts must be supported by parallel investments in digital infrastructure, workforce development, and cultural change at the institutional level.

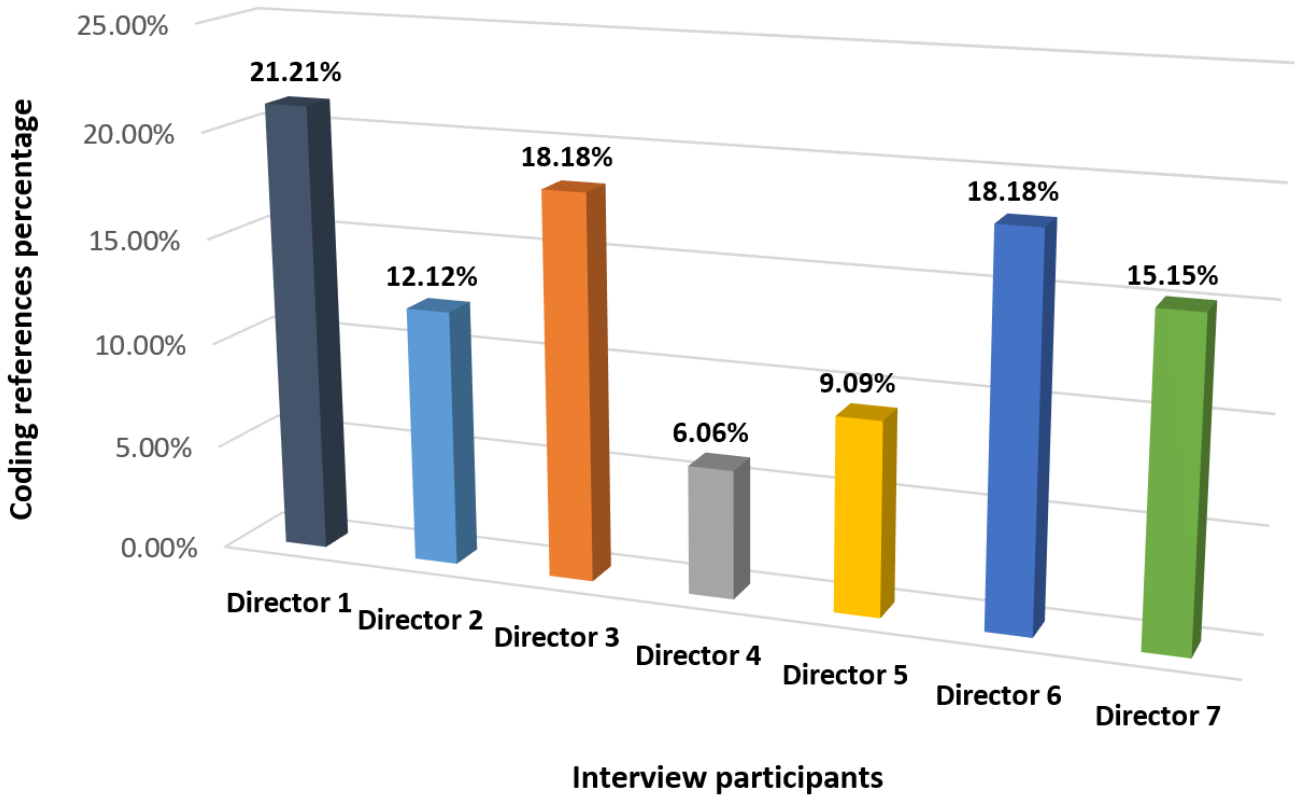

Figure 14.
Potential risks Sub-Theme Coding Rate.

Some ports reported efforts to overcome these challenges through internal training programs and partnerships with universities and research centers, as shown in Figure 15: Institutional Adaptation Strategies from Interview Data.

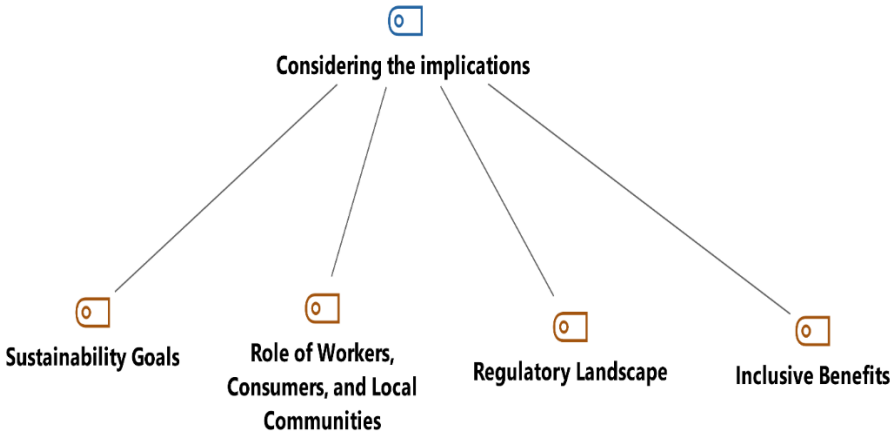

Figure 15.
Theme and sub-themes for research question 4.

4.2.5. Digital Readiness Variance

One of the key themes that emerged from the interviews was the considerable variation in digital readiness across different Egyptian ports. As shown in Figure 16, ports such as Alexandria and Ain Sokhna were perceived as relatively advanced in their adoption of data analytics and predictive systems, whereas others—like Safaga and Adabiya—were reported to face persistent financial and technological constraints that limit their ability to integrate AI.

This disparity reflects deeper structural inequalities in digital investment and institutional capacity within the national port system. Participants from more developed ports emphasized the benefits of early digital initiatives, such as smart scheduling and cargo flow tracking, which have laid the foundation for smoother AI integration. In contrast, respondents from less-equipped ports described difficulties related to outdated IT infrastructure, limited internet connectivity, and a lack of qualified technical staff.

This theme highlights a critical challenge in the national implementation of AI: the risk of uneven adoption leading to a fragmented logistics system. Without coordinated policies and targeted support, digitally lagging ports may fall further behind, weakening the overall performance and integration of Egypt's port network. The interview data reinforce the need

for a differentiated strategy—one that not only promotes innovation in high-performing ports but also allocates resources and capacity-building efforts to those struggling to meet the basic requirements of digital transformation.

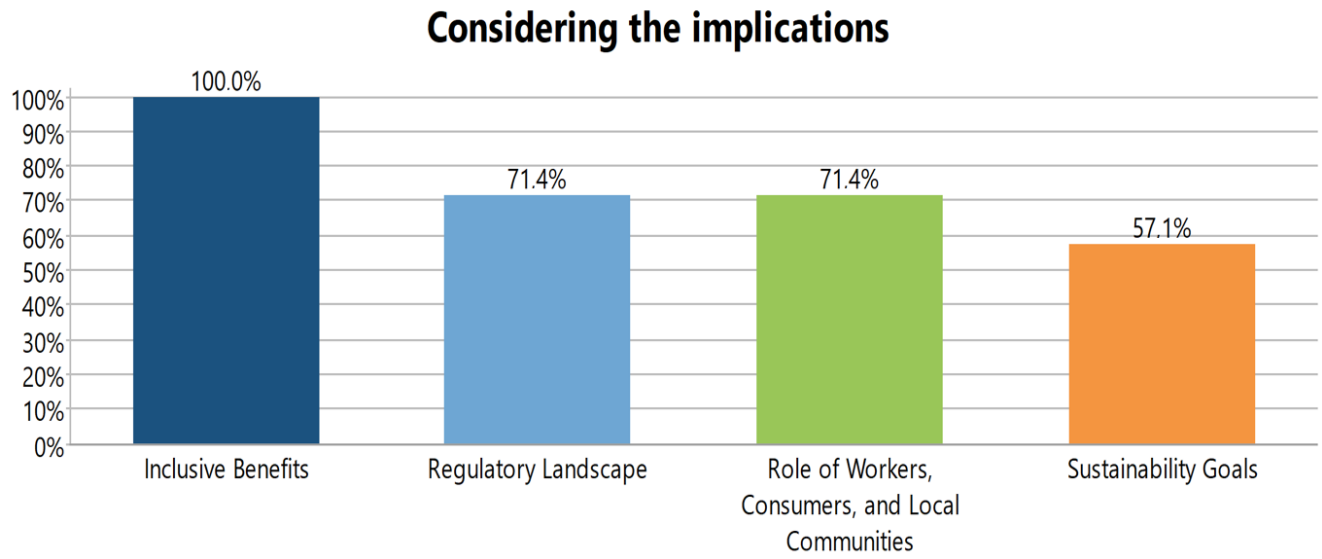

Figure 16.
Percentage of each sub-themes.

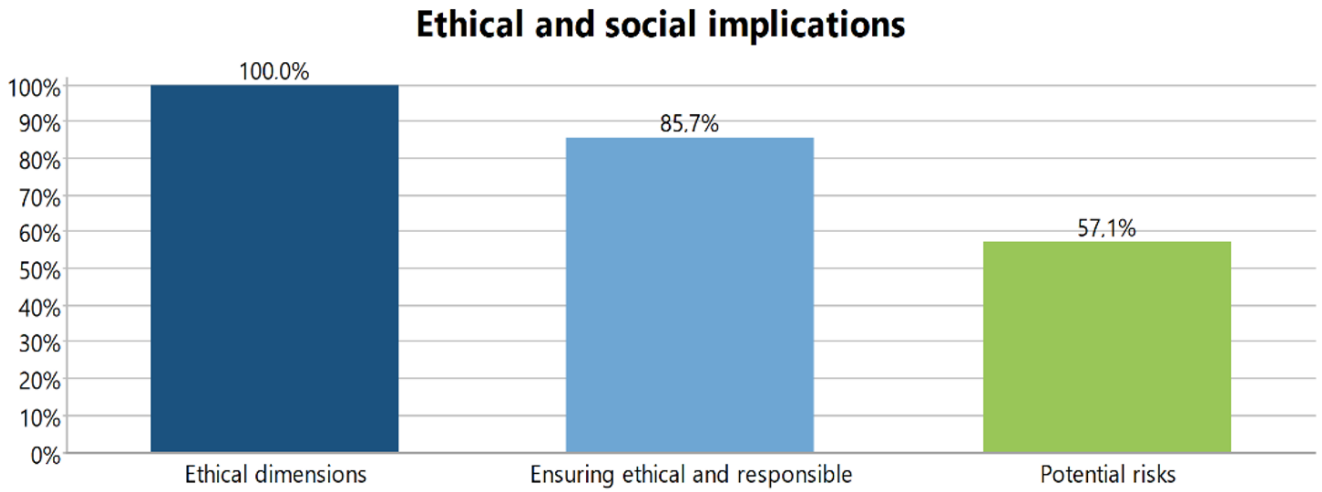

Figure 17.
Percentage of each sub-theme.

Overall, the qualitative findings suggest that managers' perceptions of AI extend beyond its technical aspects to include organizational and cultural dimensions. Many emphasized the importance of governance and policy updates, reflecting a mature understanding of digital transformation.
In sum, the interviews provided strong support for the survey results, underscoring the critical role of managerial leadership and institutional infrastructure in realizing the full benefits of AI technologies in the port environment.

5. Discussion

In recent years, interest in applying artificial intelligence (AI) in supply chain management—especially in maritime transport—has grown significantly due to the vital role of ports in global trade. Research has shown that AI can enhance operational efficiency through vessel movement prediction, automation, and big data analytics [19, 20]. It also supports decision-making and strengthens supply chain resilience [21]. Furthermore, studies highlight that AI and digital transformation are key to improving port performance and coping with disruptions [22, 23]. However, most of this research focuses on advanced ports in Asia and Europe, while limited attention has been given to developing countries, particularly in the Arab region. This study addresses that gap by exploring AI applications in Egyptian ports and evaluating their impact on supply chain performance in terms of efficiency, cost, and service speed.

6. Conclusion

This study showed that using artificial intelligence (AI) in port and supply chain operations in Egypt helps improve efficiency, speed, and accuracy. Based on both survey results and interview responses, it became clear that AI supports

faster decision-making, lowers costs, and improves how containers are handled and scheduled. The findings also show a change in how AI is viewed by managers. It is no longer seen as just a helpful tool but as something important to the way ports are managed. However, the use of AI is not the same across all Egyptian ports. Some ports still face problems like weak digital systems, limited training, and different levels of readiness. The study highlights the need to match AI use with the actual working conditions in each port. Dealing with these internal issues and recognizing the differences between ports is necessary to get the full benefits of these technologies. These results also match what other international studies have found about the value of AI in improving port operations. At the same time, the Egyptian setting presents its own special challenges, which need careful planning and support to make AI work successfully.

7. Recommendations

The successful adoption of artificial intelligence in Egyptian ports depends on addressing a number of interrelated challenges that were clearly identified in the study. One of the most pressing issues is the gap in technical infrastructure, which continues to hinder the practical application of smart technologies. In this context, the development of AI-powered maintenance and monitoring systems could play a vital role in improving operational reliability and reducing downtime, especially in ports with aging equipment and limited digital capacity.

Equally important is the need to invest in human capital. Many participants noted that the lack of training and digital skills among port staff weakens the effectiveness of AI tools. Therefore, prioritizing structured and ongoing training programs can help build digital confidence and support a smoother integration of intelligent systems into daily operations.

The study also revealed that effective AI implementation requires more than just technology—it calls for institutional and regulatory readiness. Establishing a clear and adaptive policy framework that addresses ethical use, data protection, and system accountability will ensure that AI technologies are deployed in a safe and responsible manner. Without such guidelines, the adoption process may remain fragmented or face
resistance at various organizational levels.

Finally, overcoming these challenges demands coordinated efforts across both public and private sectors. By encouraging collaboration, sharing resources, and promoting joint innovation, stakeholders can accelerate digital transformation in the port sector and create an environment where AI becomes a practical and strategic part of everyday port operations.

7.1. Contribution of the Study

1. It is one of the first studies to address the impact of AI on port performance in Egypt.
2. It provides a scientific framework that combines both quantitative and qualitative analysis to evaluate the effectiveness of AI implementation.
3. The study contributes to guiding public policies towards more sustainable AI applications in supply chains.
4. It offers primary field data that reflects the Egyptian context and enriches the literature in the Arab region.

7.2. Limitations

1. The reliance on a single case study limits the generalization of the results.
2. The data collection period was relatively short and does not cover extended time variations.
3. The varying levels of AI maturity among the participating companies affected the comprehensiveness of the analysis.

7.3. Suggestions for Future Research

This study focused primarily on the operational effects of AI in Egyptian ports, but future research could explore areas that were beyond its scope. For example, the social and economic impacts of AI on port workers—such as changes in job roles or required skills—deserve further investigation. Additionally, research into how AI contributes to environmental sustainability in port operations could offer useful insights, especially as global attention grows on green logistics. Future studies may also compare different types of ports to better understand how organizational context affects AI adoption and performance outcomes.

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