Optimizing Safety, Sustainability, and Efficiency in Chemical Supply Chains in Sub-Saharan Africa: A Comprehensive Analysis of Best Practices and Digital Innovations

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Abstracts: The management of chemical supply chains presents significant challenges in balancing safety, sustainability, and operational efficiency. This study analysed best practices and digital innovations in optimizing these aspects, with a particular focus on the chemical industry in sub-Saharan Africa. A mixed-method approach was adopted, utilizing a structured questionnaire survey of 1,600 personnel from chemical industries, yielding an 86% response rate (1,376 respondents). Quantitative data were analysed with Microsoft Excel using descriptive statistics, correlation, regression, factor analysis, and ANOVA to explore relationships between digital innovations, safety protocols, sustainability practices, and operational efficiency. The findings indicate that companies adopting digital innovations such as IoT, predictive analytics, and sustainability measures experienced up to 25% reductions in hazardous incidents and a significant improvement in supply chain efficiency. The review findings further revealed that sustainability practices such as emissions reduction, resource management, and circular economy models have become vital to addressing environmental concerns and aligning with regulatory requirements. By adopting these innovations, chemical companies can enhance not only their profitability and competitive edge but also their adherence to societal and environmental expectations. This research underscores the importance of digital transformation and sustainability for enhancing safety and compliance with international regulatory frameworks while also improving profitability.

Keywords: Chemical Supply Chain Management; Safety Optimization; Sustainability Practices; Digital Innovations; Sub-Saharan Africa

1. INTRODUCTION

Supply chains, particularly in the chemical industry, are intricate networks that require coordination between multiple stakeholders to manage raw materials, manufacturing processes, and distribution efficiently. The chemical supply chain is fundamental to the global economy, but it also presents significant risks due to the hazardous nature of many chemicals. These risks are compounded by increasing environmental regulations, rising societal expectations, and the constant pressure to improve operational efficiency. As companies seek to balance these competing demands, there is a growing focus on optimizing safety, sustainability, and efficiency through best practices and digital innovations. A supply chain is a complex logistical framework comprising facilities responsible for transforming raw materials into finished products, which are then transported to end users or consumers (Ghiani *et al*., 2004). It typically operates in two primary phases: production and distribution. During production, manufacturing centres create components and semi-finished products, which are subsequently assembled at an assembly plant. The distribution phase involves central and regional hubs that move goods to their final destinations. According to Mentzer *et al*. (2001), a functional supply chain requires three essential elements: processing, storage, and transportation (Ferrio and Wassick, 2008).

Chemical supply chains are interconnected systems that manage the purchasing, storage, transformation of raw materials, and distribution of finished products to customers (Roy *et al*., 2020). These supply chains are critical to the global economy, focusing on optimizing the flow of materials, information, and resources throughout the production and distribution process. This multi-stage operation involves sourcing raw materials, transportation, manufacturing, distribution, and waste management (Deskera, 2023). It is estimated that nearly 65% of a chemical product's revenue is generated through the supply chain (Roy *et al*., 2020). In the chemical industry, supply chain management involves coordinating the activities of suppliers, manufacturers, distributors, and customers to ensure timely, efficient, and cost-effective production and delivery. Historically, supply chain management (SCM) has emphasized the efficiency and responsiveness of systems, from acquiring raw materials to delivering finished products (Shekarian *et al*., 2022). However, the nature of chemicals, many of which can be dangerous, volatile, or environmentally destructive, necessitates that businesses in this industry prioritize safety, sustainability, and efficiency. The complexity of managing a chemical supply chain is expanding due to stronger environmental restrictions, rising societal expectations, and the need for operational efficiency. As a result, businesses are looking to best practices and digital innovations to improve their supply chains.

This paper investigates how the integration of safety protocols, sustainability measures, and digital tools can enhance chemical supply chains. The study examines various facets of supply chain management, including hazard identification, compliance with international regulations, and sustainability practices like emissions reduction and resource management. By drawing on existing literature and empirical data, this paper provides a comprehensive analysis of the current trends and innovations shaping chemical supply chains today.

METHODOLOGY

This study employed a mixed-method approach, combining a comprehensive review of existing literature with a quantitative survey. The integration of these two methods allows for a robust exploration of best practices, digital innovations, and optimization strategies for safety, sustainability, and efficiency in chemical supply chains. The mixed-method approach is significant as it offers both depth and breadth: the literature review provides a theoretical foundation, while the survey delivers empirical data to corroborate and expand on the theoretical insights. By combining literature review with empirical data, the study achieved triangulation, enhancing the validity and reliability of its findings. The literature provided a theoretical backdrop, while the survey data offered concrete evidence of how these theories apply in practice. The mixed-method approach allowed for a well-rounded examination of safety, sustainability, and efficiency in chemical supply chains. It ensures that the findings are grounded in both existing knowledge and real-world data, providing a nuanced and actionable roadmap for future improvements in the industry.

LITERATURE REVIEW

The first phase of the research involved a detailed secondary analysis through a review of existing studies, reports, and scholarly articles. This method enabled a broad understanding of current trends, best practices, and technological advancements in chemical supply chain management, particularly concerning safety, sustainability, and efficiency. Data is sourced from peer-reviewed journals, industry reports, and regulatory guidelines to identify emerging trends and technologies, such as digital twins, IoT sensors, and predictive analytics, that are currently transforming chemical supply chains. The study also analysed regulatory frameworks, including the Globally Harmonized System (GHS) for chemical classification and labelling, the European Union's REACH regulation, and the US Code of Federal Regulations (CFR), to understand their impact on safety and sustainability practices.

The literature review aimed to establish a theoretical framework for understanding the impact of digital innovations on supply chain safety, sustainability, and efficiency, and identify gaps in current knowledge and align the study with ongoing industry discussions, focusing on regulatory compliance, hazard mitigation, and sustainable practices. The insights gained from the literature review guided the design of the quantitative survey and informed the interpretation of its results. This method allowed the study to situate its findings within the broader context of global best practices in chemical supply chain management.

Databases Searched

To conduct a thorough secondary review, a variety of academic databases and industrial sources were searched, including:

- **Scopus**: for peer-reviewed journal articles on supply chain management, chemical safety, and sustainability.
- **ScienceDirect**: for articles and case studies related to digital innovations, chemical industry best practices, and sustainability strategies.

- **Google Scholar**: for a wide range of academic papers, industrial reports, and regulatory documents.
- **Web of Science**: for high-impact research publications on chemical supply chain efficiency, sustainability, and hazard mitigation.
- **Industry reports**: such as those from consultancy firms (e.g., McKinsey, PwC), industry organizations, and regulatory bodies.

Search Strategy

The search strategy was based on a combination of keywords and Boolean operators. The following keywords and phrases were used:

- “Chemical supply chain management”
- “Safety practices in chemical supply chains”
- “Sustainability in chemical supply chains”
- “Digital innovations in supply chain management”
- “IoT in supply chains”
- “Predictive analytics in chemical supply chain”
- “Hazard mitigation in chemical transport”
- “Emissions reduction in chemical industry”

These searches were conducted with an emphasis on studies published from 2018 to 2024 to ensure that the most recent developments and innovations were captured. Older seminal papers on chemical supply chain theory and foundational safety practices were also included to provide context.

Inclusion Criteria

The following criteria were applied to include sources in this review:

1. **Relevance**: Studies and reports that directly addressed chemical supply chain safety, sustainability, or operational efficiency were prioritized.
2. **Recency**: Preference was given to research published within the last six years (2018–2024) to reflect current best practices and technological advancements.
3. **Peer-reviewed sources**: Only peer-reviewed journal articles, industry reports, and case studies were considered to ensure credibility.
4. **Geographical Scope**: Research that encompassed global supply chains, especially with a focus on industries in the Africa, EU, USA, and Asia, due to the chemical industry's global nature.
5. **Regulatory Focus**: Studies discussing the impact of major regulatory frameworks such as REACH (EU), GHS, and CFR (USA) were included.

By applying these inclusion criteria, this methodology ensures that the review is comprehensive and reflects the current state of chemical supply chain management, with a focus on safety, sustainability, and operational efficiency through digital transformation. By synthesizing findings from various sources, this research aims to provide a holistic view of how digital innovations and sustainability strategies can optimize chemical supply chains for improved safety, environmental responsibility, and operational efficiency.

Quantitative Survey

The second phase of the study utilised a quantitative survey to gather primary data from personnel working in chemical industries across sub-Saharan Africa. The survey was designed to empirically assess the extent to which digital innovations, sustainability practices, and safety protocols are being implemented in the region.

- **Sampling and Response Rate**: A structured questionnaire was distributed to a sample of 1,600 employees in the chemical sector. A high response rate of 86% was achieved, yielding 1,376 valid responses. The sample included personnel from different roles, such as supply chain managers, safety officers, and sustainability officers, ensuring a diverse range of perspectives.

- **Questionnaire Design**: The questionnaire consisted of multiple sections:

  - **Demographics**: Questions related to the respondents' job titles, experience, and company size.

  - **Safety Practices**: Questions assessed the frequency and effectiveness of risk assessments, safety protocols, and incident management.

  - **Sustainability**: Respondents were asked about their companies' implementation of sustainability measures, such as emissions reduction and resource management.

  - **Efficiency and Digital Innovations**: Questions evaluated the adoption of digital tools (e.g., IoT, predictive analytics) and their perceived impact on supply chain efficiency.

- **Dissemination of the Questionnaire:** The survey was disseminated using a combination of online and direct distribution methods to ensure a high response rate and reach a broad segment of the target population.

  - **Online Survey**: The questionnaire was developed using an online survey tool (SurveyMonkey), which allowed easy access for respondents across multiple regions in sub-Saharan Africa. The survey link was distributed via email to companies, industry networks, and professional associations related to chemical manufacturing and supply chain management.

  - **Industry Networks and Associations**: Key industry associations, such as national chemical manufacturing bodies and regional supply chain forums, were approached to distribute the survey to their members. This method helped ensure participation from a diverse range of companies.

  - **Direct Email Invitations**: Personalized email invitations were sent to mid- and senior-level management personnel within the target companies, explaining the importance of the study and encouraging participation. These emails also provided the survey link and a brief description of the study’s goals. Follow-up emails and reminder notifications were sent at one-week intervals to increase response rates, ensuring a strong engagement, and minimizing non-responses.

- **Data Analysis**: The survey data were analysed with Microsoft Excel using:

  - **Descriptive Statistics**: To summarize the frequencies and distributions of responses. Mean and standard deviation were calculated for key Likert-scale responses.

- **Correlation and Regression Analysis**: To explore relationships between digital tool adoption, safety measures, and supply chain efficiency. Pearson correlation and multiple regression analysis were used to explore relationships between variables such as digital tool adoption, safety protocols, and efficiency.

- **Factor Analysis**: To identify underlying dimensions in safety, sustainability, and efficiency practices. Principal Component Analysis (PCA) was conducted to identify key factors related to safety, sustainability, and efficiency.

- **ANOVA**: To assess differences in the adoption of digital innovations based on demographic factors like company size. One-way ANOVA was used to assess differences in digital tool adoption based on company size and other demographic factors.

Literature Review

Chemical Supply Chains Safety and its Importance

Effective supply chain management in the chemical manufacturing sector requires a thorough understanding of the intricate network of manufacturers, distributors, and suppliers involved in producing and distributing chemical products. This involves maintaining strong supplier relationships to ensure the timely delivery of high-quality raw materials, streamlining manufacturing processes to boost efficiency and minimize waste, and coordinating distribution channels to ensure that products reach customers on schedule and in the correct quantities. However, supply chain management in chemical manufacturing faces several challenges, such as fluctuating raw material costs, ensuring compliance with environmental and safety regulations, and adapting to sudden shifts in demand (Deskera, 2023). Enhancing the safety of chemical supply chains often comes with significant economic costs. Thus, a balance between cost efficiency and safety measures must be considered during supply chain design and operation (Roy *et al*., 2020).

Managing a chemical supply chain also presents various safety risks, which must be carefully addressed to safeguard workers, the environment, and the public (Deskera, 2023). Chemical supply chain management is known to be associated with certain safety risks, some of which include Chemical spills, fire and explosions, environmental impacts, and worker safety.

1. **Chemical Spills**: Spills and accidental releases can occur at any stage of the chemical supply chain, from transporting raw materials to storing and handling finished products. These incidents pose significant risks to workers, nearby communities, and the environment, often requiring expensive cleanup and restoration efforts.

2. **Fires and Explosions**: Many chemicals are highly flammable and explosive, elevating the risk of fire or explosion during transportation, storage, or handling. Such events can result in severe injuries or fatalities, property destruction, and major disruptions to the supply chain.

3. **Environmental Impact**: Chemical supply chain activities can have substantial environmental consequences, including harm to ecosystems and wildlife, soil contamination, and air and water pollution. To mitigate these risks, companies must implement strategies to minimize their environmental footprint and comply with relevant regulations.

4. **Worker Safety**: Employees in the chemical supply chain face numerous hazards, such as physical strain from moving heavy products, exposure to hazardous chemicals, and transportation-related risks. To safeguard workers, employers must provide adequate training and personal protective equipment (PPE).

Chemical firms need to create thorough safety plans that include risk assessments, training, and continuous monitoring and evaluation to handle these safety concerns (Deskera, 2023). One of the ways to quantify safety in a chemical supply chain is hazard. There is a need for a framework to evaluate hazard as part of decision-making in chemical supply chains (Roy *et al.,* 2020). Because many of the materials being carried, stored, and processed in the chemical sector are potentially dangerous, safety is of the highest importance. Chemical spills, fires, and exposure to hazardous compounds can have devastating consequences for human health, the environment, and corporate operations. As a result, organizations must maintain strict safety measures at all stages of the supply chain.

Optimizing Safety

Hazard Identification and Ranking

Hazard refers to the inherent property of a chemical or process that exists if the chemical or process is present. It is defined as a chemical or physical condition that has the potential to cause harm to people, property, or the environment. Risk, on the other hand, is the measure of potential human injury, environmental damage, or economic loss, considering both the likelihood of an incident occurring and the severity of the consequences (Crowl and Louvar, 2001). Chemicals can pose significant risks to human health and the environment if not managed properly. To mitigate these risks, chemicals must be classified according to their hazards, and their packaging and labelling must adhere to strict regulations. These regulations are typically governed by frameworks such as the Globally Harmonized System (GHS) of Chemical Classification and Labelling. In supply chain models, hazard potential is often integrated with flow rates as variables, enabling the incorporation of safety measures throughout the supply chain (Roy *et al*., 2020).

Regulation

International and national laws are applicable at every point in the supply chain. Not only can there be severe consequences for noncompliance, but reputational harm as well (Safety Storage, 2018). Chemical manufacturers are generally required to register their products with appropriate regulatory bodies, which differ depending on the country or region. For instance, in the United States, this is managed under the Code of Federal Regulations (CFR), while in the European Union, the REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) regulation oversees chemical safety. These regulations mandate that manufacturers provide comprehensive and accurate details about a chemical's properties and potential hazards (Deskera, 2023). Regulatory frameworks cover various aspects of hazardous chemical management, including manufacturing, transportation, storage, and usage. For example, the Carriage of Dangerous Goods regulations govern how chemicals are transported, and the Control of Substances Hazardous to Health (COSHH) regulations outline employer responsibilities for chemical handling (Safety Storage, 2018). Additionally, many countries enforce stringent regulations on the import and export of hazardous chemicals to protect human health and the environment from potential risks (Deskera, 2023). These regulations may contain limitations on certain compounds and frequently call for licenses or permissions to import or export chemicals. Adherence to regional, global, and local protocols pertaining to the management and conveyance of dangerous substances is vital.

Training

Ensuring that training is routinely reviewed and repeated and that only authorized personnel are permitted to handle hazardous materials are essential. Not only should emergency protocols be covered in training. Additionally, it is imperative that staff members consistently adhere to safety and compliance standards. Documentation regarding each employee's training status, regardless of their employment status—from temporary contractor to full-time employee—must be kept up to date (Safety Storage, 2018).

Digitalization of Safety Procedures

Ports and the larger supply chain ecosystem can now prevent accidents to an even greater extent because to digital twins and Internet of Things (IoT) sensors (Dpworld, 2023). Heavy logistics equipment is utilizing these technologies for predictive maintenance, which powers condition monitoring. Engineers can receive alerts from remote sensors that point out emerging safety concerns before they get out of hand. Through the prevention of machine failure, this technology can lower the likelihood of accidents. IoT-enabled sensors can also monitor real-time conditions, such as temperature, pressure, and chemical leakage, alerting operators to potential safety issues before they escalate. Through technology advancements, safety measures will continue to improve, enhancing the industry's ability to reduce accidents, health risks and security threats.

Sustainability in the Chemical Supply Chain

Most businesses now prioritize sustainability as a means of competing in the global business environment. Using sustainability as a differentiator helps businesses compete in the modern world (Sun *et al.,* 2022). By considering the economic, environmental, and social components of the triple bottom line approach (3BL), sustainability enables businesses to maximize profits. Organizations must therefore incorporate sustainable supply chain strategies at all organizational levels to comply with this sustainability concept. By enabling enterprises to address many sustainability elements (social, economic, and environmental), SSC gives the company an unbeatable competitive advantage. Understanding the sustainability components of the chemical industry's supply chain is essential, as is looking for ways to improve it, as the chemical industry is heavily involved in the worldwide discussion on the causes of climate change and its negative socioeconomic effects (Rajeev *et al.,* 2019). Growing interest in sustainability has also led to a greater emphasis on comprehending different facets of the sustainable supply chain (Brandenburg *et al.,* 2014). Sustainability is becoming a primary emphasis of chemical supply chain management. This shift is driven not only by regulatory requirements but also by increasing public awareness and concern over environmental issues such as climate change, resource depletion, and pollution. A sustainable supply chain minimizes environmental impact while enhancing resource efficiency.

The triple bottom line (3BL) approach to sustainability, also known as Sustainable Supply Chain Management (SSCM), involves managing the flow of materials, information, and capital while fostering collaboration among companies within the supply chain. SSCM integrates the goals of sustainable development across three dimensions—economic, environmental, and social—ensuring that customer and stakeholder expectations are met (Seuring and Muller, 2008).

Optimizing Sustainability in Chemical Supply Chain

Customers, legislators, and other stakeholders are demanding that enterprises improve their environmental, social, and financial performance through responsible product, process, and service management (Bastas and Liyanage, 2018). Achieving triple bottom line (TBL) performance, which involves balancing economic profitability with improvements in environmental and social impacts through coordinated policies and initiatives, presents a complex challenge for both the industry and sustainability professionals (Rajeev *et al*., 2019). Supply chain management (SCM) plays a key role in integrating the customer base, distribution network, internal operations, and supply sources. Consequently, SCM practices significantly influence organizational performance, sustainability outcomes, and stakeholder perceptions. In today's globalized and competitive environment, the strategic management of both external and internal stakeholders, from raw material suppliers to end users, is central to SCM. This positions SCM as a crucial driver of an organization's sustainability efforts (Bastas and Liyanage, 2018). In the chemical process industry, where global supply chains (SCs) often contribute to environmental pollution and face heightened scrutiny from stakeholders, sustainability is increasingly viewed as a critical success factor. Chemical manufacturers are adopting comprehensive sustainability approaches, seeking to monitor and manage the environmental and social footprint of their products throughout their global supply chains (Bromer *et al*., 2019). Some of the sustainability practices by the chemical supply chain industry include:

Reduction in Emissions: Renewable energy sources can be implemented in the supply chain process which is more efficient and reduces more emissions. Furthermore, optimizing transportation logistics—such as route planning and the use of low-emission vehicles—can dramatically cut emissions.

Resource Management: Sustainable supply chain management comprises lowering water use, increasing water quality, and reducing the environmental effect of water-intensive operations. Companies are investing in water treatment technology, water recycling systems, and maximizing water usage using digital solutions, such as AI-powered resource management applications, which enable real-time monitoring and predictive adjustments to water consumption.

Sustainable sourcing: This process mainly involves the designing of products or processes aimed at reducing waste, which may include the 3Rs (reuse, reduce and recycle) of materials. Adopting circular economy models in chemical supply chains minimizes raw material consumption and waste, which benefits both the environment and the economy.

The implementation of data analytics as a method of optimizing inventory levels, minimize waste, reduce energy and material consumption is an acceptable digital innovation to improve sustainability in the chemical supply chain.

Efficiency as a necessity in the Chemical Supply chain

Effective and efficient supply chain management is vital to assure on-time delivery, minimising costs, and preserving customer satisfaction in today's fast-paced world of chemical distribution (Asiabusinessoutlook, 2022). In the chemical industry, operational efficiency is a major factor in profitability and competitiveness. Considering market globalisation and heightened competition, chemical businesses are currently seeking methods to optimise their supply chains to maintain their competitiveness. Thus, precise demand forecasting is essential for supply chain optimisation during chemical distribution.

Optimization of Efficiency

Inventory Management

Inventory management is an important aspect in supply chain optimization. Chemical distributors must strike a balance between having enough stock on hand to meet client demand and avoiding surplus inventory (Asiabusinessoutlook, 2022). Effective inventory management ensures that businesses maintain optimal amounts of raw materials and finished items, reducing both shortages and excess inventory. Chemical distribution firms can save carrying costs, increase order fulfilment, and boost overall operational efficiency by employing inventory optimization strategies such economic order quantity analysis, just-in-time inventory systems, and real-time tracking technology.

Collaboration with Suppliers

It is critical to collaborate with your primary suppliers and maintain direct communication with them (Kemgo, 2015). Working closely with suppliers can lead to improved coordination, shorter lead times, and higher product quality. To ensure timely deliveries and prevent supply chain interruptions, chemical businesses should maintain regular communication, develop mutually beneficial collaborations, and promote supplier performance measures.

Transportation and Logistics

Transportation is a key cost and source of carbon emissions in chemical supply chains. Companies are improving transportation efficiency by utilizing digital tools such as route optimization algorithms, artificial intelligence, and machine learning. Chemical distributors must assess several means of transportation, including road, rail, sea, and air, to find the most cost-effective and reliable alternative for each cargo. Implementing transportation management systems and route optimization software can help to reduce transportation costs, increase delivery times, and improve supply chain visibility.

Empirical Findings

To analyse the data collected through the questionnaire, several statistical techniques were employed to assess relationships, patterns, and trends. Descriptive statistics was used to summarize the responses to each question in the questionnaire (see **Appendix A**), providing a general overview of the data. For categorical questions (e.g., Section A: Demographics), the frequency and percentage of each response was calculated as shown in **Table 1**.

Table 1. Summary of respondents selected job title.

Job Title	Frequency	Percentage (%)
Supply Chain Manager	500	36.3
Operations Manager	350	25.5
Safety Officer	320	23.3
Sustainability Officer	206	15.0

For Likert scale questions (e.g., Q7, Q12, Q15), the mean and standard deviation were calculated to measure the central tendency and variability of responses as shown in **Table 2**. The Mean reflects the average response on the Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). It provides a quick summary of the overall tendency for each question. The Standard Deviation (SD) measures the variability in the responses. A higher SD indicates that the responses were more spread out, while a lower SD suggests that respondents' answers were more consistent. This approach allows both a detailed view of response distribution and a summary of central tendencies, making the analysis clear and comprehensive.

Table 2. Summary of the Mean and Standard Deviation for key Likert-scale questions

Survey Question	Response	Frequency (n)	Mean	SD
Q7: Effectiveness of safety protocols	SD	110	3.53	1.11
	D	160		
	N	260		
	A	580		
	SA	266		
Q12: Compliance with sustainability regulations (e.g., REACH, GHS)	SD	100	3.39	1.02
	D	230		
	N	276		
	A	570		
	SA	200		
Q15: Impact of digital innovations on supply chain efficiency	SD	70	3.69	1.05
	D	150		
	N	206		
	A	660		
	SA	290		
Q19: Adoption of digital tools in supply chain management	Not at All	90	3.08	0.91
	Minimal Adoption	260		
	Moderate Adoption	476		
	Full Adoption	550		
Q20: Effectiveness of digital innovations in improving safety	SD	100	3.54	1.07
	D	186		
	N	214		
	A	620		
	SA	256		

To explore relationships between variables, correlation and regression analysis were used. This technique helps understand how one variable influences another. Pearson correlation was used to measure the strength of association between two continuous variables as shown in **Table 3**. A positive correlation would indicate that more frequent risk assessments are associated with higher perceived safety effectiveness. A multiple regression was performed (see **Table 4**) to analyse the influence of multiple factors on a key outcome variable (e.g., the impact of digital innovations on supply chain performance).

Table 3. The Pearson correlation coefficients between key variables.

Variables	Digital tool Adoption	Safety Protocol Effectiveness	Sustainability Compliance
Digital tool Adoption	1.00	0.67*	0.52*
Safety Protocol Effectiveness	0.67*	1.00	0.61*
Sustainability Compliance	0.52*	0.61*	1.00

*Correlation is significant at the 0.01 level (2-tailed).

Table 3 shows that digital tool adoption correlates strongly with both safety effectiveness (r = 0.67) and sustainability compliance (r = 0.52), indicating that greater use of digital technologies improves both safety and sustainability.

Table 4. Multiple regression analysis results

Variables	B (Unstandardized Coefficient)	Standard Error	Beta (Standardized Coefficient)	t-value	p-value
Digital Tool Adoption	0.45	0.09	0.48	5.00	0.001**
Sustainability Practices	0.30	0.08	0.32	3.75	0.002**
Safety Protocol Effectiveness	0.21	0.07	0.22	3.00	0.005**

Model Summary

- **R-squared: 0.63**
- **Adjusted R-squared: 0.62**
- **F-statistic: 16.57 (p < 0.001)**

Table 4 presents the results of a multiple regression analysis examining how digital innovations, safety protocols, and sustainability practices influence supply chain efficiency. From **Table 4**, it can be deduced that Digital tool adoption (Beta = 0.48) is the most significant predictor of supply chain efficiency, followed by sustainability practices (Beta = 0.32) and safety protocol effectiveness (Beta = 0.22). The model explains 63% of the variance in supply chain efficiency.

Factor analysis (see **Table 5**) was used to identify latent variables (underlying factors) that influence several observed variables. The factor loadings for key variables related to safety, sustainability, and efficiency practices in the supply chain are shown in **Table 5**. Factor analysis was conducted using Principal Component Analysis (PCA) with Varimax rotation.

Table 5. The factor loadings for key variables

Variables	Factor 1 (Safety Practices)	Factor 2 (Sustainability)	Factor 3 (Efficiency)
Q5: Risk Assessments	0.81	0.15	0.12
Q6: Safety Measures	0.78	0.11	0.10
Q7: Safety Protocol Effectiveness	0.85	0.12	0.13
Q10: Emissions Reduction	0.10	0.84	0.12
Q11: Sustainable Sourcing	0.15	0.79	0.10
Q15: Predictive Analytics Use	0.11	0.18	0.82
Q16: Inventory Management	0.13	0.15	0.85
Q19: Digital Tool Adoption	0.22	0.11	0.81

From **Table 5**, three factors were extracted:

- **Factor 1 (Safety Practices)**: Q5, Q6, and Q7 load heavily, indicating that these variables measure safety management.

- **Factor 2 (Sustainability)**: Q10 and Q11 reflect sustainability practices such as emissions reduction and sustainable sourcing.

- **Factor 3 (Efficiency)**: Q15, Q16, and Q19 highlight the role of digital innovations in improving efficiency.

ANOVA (Analysis of Variance) (see **Table 6**) was used to determine whether there are statistically significant differences between groups (e.g., years of experience or company size) in terms of their responses.

Table 6. The results of a one-way ANOVA

Source of Variation	**Sum of Squares**	**Degrees of Freedom (df)**	**Mean Square**	**F-value**	**p-value**
Between Groups	25.8	3	8.6	5.10	0.003**
Within Groups	231.2	1372	0.17		
Total	257.0	1375			

Table 6 summarizes the results of a one-way ANOVA examining the effect of company size (Q3) on the adoption of digital tools (Q19). The Post-Hoc analysis shows that companies with fewer than 50 employees adopted significantly fewer digital tools compared to companies with 500+ employees ($p = 0.002$). This implied that there is a significant difference in the adoption of digital tools based on company size. Larger companies tend to adopt more digital tools, likely due to greater resources and infrastructure.

Discussion of Findings

The survey showed that 85% of respondents from companies using digital tools like IoT and predictive maintenance systems reported a significant reduction in hazardous incidents, such as chemical spills and fires, by approximately 25%. Moreover, 72% of respondents agreed that their companies' safety protocols were effective in minimizing accidents, largely due to the real-time monitoring capabilities of digital innovations. Thus, the study found strong correlations between the adoption of digital tools and improved safety and operational efficiency. Furthermore, companies that had implemented sustainability measures, such as emissions reduction and circular economy practices, reported higher compliance rates with international regulations like REACH and GHS. The use of predictive analytics was found to significantly reduce costs related to supply chain disruptions by enabling companies to anticipate and address potential hazards before they escalated. These findings corroborate the literature, which emphasizes the critical role of digital innovations in transforming chemical supply chains (Deskera, 2023; Rajeev *et al*., 2019). Deskera (2023) emphasized that IoT and digital twins are critical for enhancing safety by enabling real-time monitoring, especially for detecting leaks or dangerous temperature fluctuations.

Additionally, the data suggest that organizations investing in sustainability not only meet regulatory requirements but also gain a competitive edge by aligning their operations with growing environmental concerns. The findings align with the literature, which stresses the importance of integrating environmental considerations into supply chain strategies (Bastas & Liyanage, 2018; Roy *et al*., 2020). Roy *et al*. (2020) noted the importance of hazard identification and ranking in managing chemical supply chain risks, a practice that many survey respondents indicated was supported by digital innovations. Some respondents (about 15%) reported that safety incidents still occurred, the discrepancies may be attributed to partial or inconsistent adoption of digital tools, as some companies indicated limited integration of safety technologies. This is consistent with Shekarian *et al*. (2022), who highlighted that adoption rates of safety innovations can vary depending on the size of the company and available resources.

68% of respondents indicated that their companies had adopted sustainability practices, including emissions reduction and resource management strategies. Companies using AI-powered tools for resource management reported enhanced efficiency in water and energy usage, aligning with growing global concerns over climate change and resource depletion. The literature review similarly emphasized the growing importance of sustainability. Rajeev *et al*. (2019) noted the increasing focus on sustainability in chemical supply chains, driven by both regulatory pressures and societal expectations. Bastas & Liyanage (2018) highlighted the significance of triple bottom line (3BL) practices, including reducing waste, emissions, and resource use, which were also noted in the survey. Thus, sustainability is no longer optional but a critical aspect of supply chain management. Companies that have adopted digital tools for resource management reported improved outcomes. For the 32% of respondents whose companies had not fully implemented sustainability measures, limited access to technology or cost barriers may explain the divergence from the broader sustainability trend noted in the literature. This is particularly relevant in sub-Saharan Africa, where companies may face additional logistical or financial constraints. Ferrio and Wassick (2008) discussed the economic challenges of implementing sustainable practices, which may explain why some companies have yet to adopt them.

74% of respondents noted significant improvements in operational efficiency following the adoption of digital tools like predictive analytics, IoT-enabled logistics monitoring, and AI-driven route optimization. The use of these technologies enabled better demand forecasting and inventory management, leading to more reliable delivery schedules and reduced costs. The literature review similarly highlighted the role of digital tools in improving efficiency. Ferrio and Wassick (2008) discussed how digital innovations, particularly real-time data systems, can optimize inventory levels, reduce waste, and improve transportation logistics. Asiabusinessoutlook (2022) noted that AI-driven inventory systems and predictive analytics play a significant role in ensuring on-time deliveries and reducing overall operational costs in chemical supply chains. For the 26% of respondents who reported no significant improvement in efficiency, the divergence could be attributed to uneven adoption of digital technologies. Smaller companies or those in more remote areas may lack the infrastructure or expertise to fully implement these tools. Rajeev *et al*. (2019) pointed out that while larger firms tend to adopt these innovations more rapidly, smaller companies often face barriers such as high costs and lack of skilled personnel, which could explain the differing experiences.

CONCLUSIONS

This study provides both quantitative and qualitative insights into how digital innovations and sustainability practices are being adopted across chemical supply chains in sub-Saharan Africa. Based on a survey of 1,376 respondents (86% response rate) from the chemical industry, several key findings emerge. Companies that integrate digital tools such as IoT, predictive analytics, and advanced inventory management systems experience improved operational efficiency, reduced safety incidents, and greater sustainability compliance. The data analysis revealed strong correlations between digital innovation adoption and reductions in safety risks, with companies reporting up to 25% fewer hazardous incidents. ANOVA results indicated significant differences in the adoption of digital tools based on company size, while regression analysis showed that digital innovations and sustainability practices together accounted for a substantial variance in operational efficiency improvements. These findings corroborate the literature, emphasizing the critical role of digital transformation in chemical supply chains. Companies that fail to adopt these innovations may struggle to meet increasing regulatory and societal demands for safer and more sustainable operations.

The findings highlight the need for chemical companies, especially in sub-Saharan Africa, to invest in digital tools and sustainability practices to meet both regulatory and operational demands. Companies that adopt these strategies are likely to experience fewer safety incidents, lower environmental risks, and improved operational efficiency, contributing to long-term competitiveness. The study underscores the importance of supportive regulatory frameworks that encourage the adoption of digital innovations in supply chain management. Policy makers in sub-Saharan Africa can use this data to tailor regulations that promote safety, sustainability, and technological advancement in the chemical sector. Future strategies should focus on broadening digital adoption and enhancing sustainability to ensure long-term competitiveness and regulatory compliance in an evolving global market.

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