World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Review Article)

A cybersecurity resilience framework for underserved rural SMEs in critical infrastructure supply chains: Strengthening operational continuity and threat response in digitally vulnerable regions

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World Journal of Advanced Research and Reviews, 2024, 24(03), 3464-3477

Publication history: Received on 14 November 2024; revised on 22 December 2024; accepted on 25 December 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.24.3.3948

Abstract

Small and medium-sized enterprises (SMEs) in underserved rural regions, particularly those integrated into critical infrastructure supply chains, face heightened vulnerability to evolving cyber threats. These SMEs often lack access to specialized cybersecurity resources and expertise, posing significant challenges to their operational continuity and overall resilience. This paper proposes a cybersecurity resilience framework specifically tailored for these underserved rural SMEs. The framework aims to enhance their capacity to resist cyberattacks, ensure business continuity, and improve threat response within critical infrastructure supply chains. It addresses this risk by incorporating scalable cybersecurity solutions, leveraging local knowledge, and fostering collaboration with larger stakeholders to mitigate threats, accelerate response, and build resilience in these vulnerable regions. This article also highlights key considerations for enhancing cybersecurity awareness, training, and resource allocation to enable SMEs to navigate the digital landscape safely and efficiently.

Keywords: Cybersecurity resilience; Small-to-medium size enterprises; Critical infrastructure; Business continuity; Threat response; Digital resilience; Cybersecurity framework

1. Introduction

The ongoing digital transformation has increasingly integrated small and medium-sized enterprises (SMEs) into critical infrastructure supply chains. However, these enterprises, particularly those operating in underserved rural areas, face significant vulnerabilities to cyberattacks. While SMEs are vital to national and global economies, their cybersecurity resilience is a considerable concern in regions with low digital literacy, inadequate infrastructure, and limited access to cybersecurity resources. Rural SMEs, often overlooked in cybersecurity programs, struggle to defend against cyberattacks, system failures, and downtime, which can profoundly impact the broader supply chain.

The threat of cyberattacks extends beyond large organizations and urban centers. Rural SMEs are at high risk due to their limited access to cybersecurity skills, technologies, and training. These communities are frequently marginalized in cybersecurity policy discussions, making them particularly susceptible to malware, ransomware, phishing, and cyber warfare. Unaddressed, these vulnerabilities could have disastrous consequences, affecting not only the individual SMEs but also the larger supply chains and critical systems that depend on their operations.

For SMEs involved in sectors like agriculture, energy, transportation, and healthcare, a failure to maintain secure and resilient systems can disrupt the entire supply chain, leading to significant operational continuity losses across industries. Therefore, enhancing the cybersecurity resilience of such rural SMEs is paramount. This paper discusses the concept of cybersecurity resilience and proposes a framework designed to meet the unique needs of underserved rural

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SMEs within critical infrastructure supply chains. The article will formulate practical solutions to identified gaps, enabling these vital SMEs to build future resistance to threats and ensure operational continuity.

1.1. State of cybersecurity in rural SMEs

SMEs are typically characterized by limited financial capital and skilled knowledge. Rural SMEs are uniquely challenged by geographical distances and barriers to accessing high-level technology, as well as a scarcity of local cybersecurity professionals. This creates a digital gap, leaving them less equipped to defend against cyberattacks compared to their urban counterparts, who often have greater access to cybersecurity products and services.

The United States Small Business Administration indicates that many SMEs often neglect essential cybersecurity precautions, such as software updates, intrusion detection system installations, and employee cybersecurity education. This situation is exacerbated in rural regions, where a general lack of awareness regarding potential dangers further exposes these businesses to risks. Moreover, the highly interdependent nature of SME supply chains means that a weakness in one SME can have adverse cascading effects throughout the entire chain, potentially compromising critical infrastructure safety.

1.2. Challenges affecting rural SMEs

The unique challenges affecting rural SMEs manifest as:

- **Poor access to resources:** Compared to urban centers, rural areas have fewer cybersecurity service providers. Consequently, SMEs in these regions are often compelled to manage their cybersecurity processes with inadequate information and limited resources.
- **Insufficient cybersecurity skills:** Most rural SMEs cannot afford to employ dedicated cybersecurity expertise or invest in sophisticated tools necessary to protect against modern cyber threats.
- **Heightened attack probability:** As rural SMEs become more integrated into national and international supply chains, they face increased exposure to the same cyberattacks as larger entities, despite having a diminished capacity for prevention.
- **Poor cybersecurity awareness:** A general lack of education and awareness regarding cybersecurity best practices means many rural SMEs do not fully recognize the risks and potential impact of cyber threats.

1.3. The significance of cybersecurity resilience

Cybersecurity resilience refers to an organization's capacity to resist, detect, and recover from cyber threats, ensuring the maintenance of critical operations and the avoidance of major disruptions. Resilience extends beyond traditional, prevention-oriented cybersecurity efforts; it encompasses comprehensive planning for preparation, detection, response, and recovery.

Cybersecurity resilience is crucial for rural SMEs within critical infrastructure supply chains to ensure business process continuity, even in the aftermath of a cyberattack. These companies frequently handle confidential information and perform key functions, disruption of which can have devastating economic and societal effects. For instance, a cyberattack on a rural agricultural product distributor could destabilize the food supply chain, potentially leading to shortages and economic imbalances.

Building cybersecurity resilience involves more than just preventing attacks; it's about ensuring a business can act promptly and limit damage if an attack occurs. Key elements of cybersecurity resilience include:

- Proactive threat detection: Identifying threats and potential weaknesses before they are exploited.
- Effective response mechanisms: Developing strategies to minimize the impact of a cyberattack, such as incident response plans and disaster recovery processes.
- Continuous improvement: Regularly assessing and enhancing the cybersecurity posture in response to evolving threats and insights from past incidents.

1.4. Development of a cybersecurity resilience framework for rural SMEs

A customized cybersecurity resilience framework for rural SMEs must consider the unique problems these businesses encounter, such as resource and knowledge scarcity. The framework should be scalable, suitable for both large and small businesses across various industries, allowing for flexible adoption and support.

1.5. Essential elements of the cybersecurity resilience framework

1.5.1. Cybersecurity awareness and training programs

Most rural SMEs lack adequate awareness of the cyber threats they face. A fundamental component of a resilience framework is the systematic development of cybersecurity education and training programs. Such programs must encompass a basic understanding of cybersecurity, threat identification, and response methods, targeting not only business owners but also employees and other supply chain stakeholders. Improving the digital literacy of personnel in rural SMEs significantly enhances their ability to mitigate successful cyberattacks.

1.6. Joint actions and cooperations

Given the limited local cybersecurity expertise, rural SMEs are advised to establish partnerships with larger entities, government bodies, and cybersecurity service providers. These collaborations can provide access to essential technical support, resources, and tools. Additionally, SMEs can participate in industry-specific cybersecurity programs, facilitating the sharing of resources, intelligence, and fostering a collective defense.

1.7. Scalable cybersecurity tools

While large companies can afford cutting-edge cybersecurity technologies, rural SMEs require inexpensive and scalable solutions. The framework should recommend the use of simple but effective cybersecurity tools, such as firewalls, antivirus programs, data encryption measures, and multi-factor authentication systems. Investing in secure cloud solutions and robust backup systems is also advisable to ensure business continuity in the event of an attack.

1.8. Incident response and recovery plans

It is crucial for every SME to develop an incident response plan. This plan should clearly outline actions to be taken in the event of a cyberattack, including steps for isolating affected systems, whom to notify, and procedures for initiating the recovery process. A comprehensive disaster recovery strategy, encompassing data backup, recovery schedules, and business continuity plans, must also be integrated into the resilience framework.

1.9. Risk assessment and risk management

Rural SMEs should conduct periodic cybersecurity risk assessments to understand the potential vulnerabilities in their operations. These assessments can be performed with the assistance of cybersecurity professionals or through government and industry-led initiatives that offer free or low-cost assessments. Identifying risks enables businesses to adopt effective mitigation measures.

Table 1 The Key Elements of a Cybersecurity Resilience Framework of Rural SMEs

Component	Description	Implementation Strategy
Cybersecurity Awareness and training	Learning about threats and cybersecurity best practice.	Offer online courses, learning workshops and easy-to-read materials to SMEs.
Co-works and Partnerships	Forming partnerships with other bigger organizations and security companies.	Complete risk surveys, detect weaknesses and arrange protection strategies.
Technology and the Cybersecurity Tools	The installation of simple, low-cost cybersecurity solution	Enter into partnerships with industry groups, local governments and bigger-enterprises.
Operation of Incident Response and Recover Plans	Assessing risks posed by cybersecurity on a regular basis in terms of business operations.	Write incident response and business continuity plans and set out steps.
Risk Evaluation and control	Risk Evaluation and control	Complete risk surveys, detect weaknesses and arrange protection strategies.

The digital vulnerability of rural smaller enterprises in this key supply chain is a burning problem that is subject to urgent revision. With the help of the custom cybersecurity resilience model, these enterprises will be able to reinforce their business resilience and threat response in many aspects. This structure should be scalable and financially viable, sensitive towards the rural SMEs peculiarities and aims at developing the awareness of cybersecurity issues, establishing partnerships, and incorporating the newest technologies to protect themselves against the technological threats. The subsequent sections of this paper will delve deeper into specific methods for building resilience in underserved rural areas and discuss relevant technologies, along with examples of successful framework implementations.

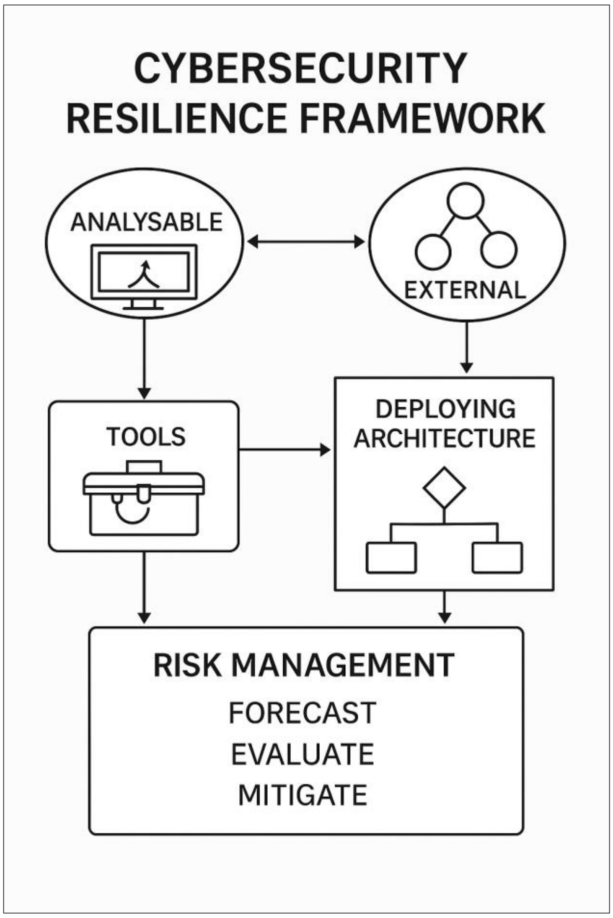


Figure 1 A model of improving the cybersecurity resilience among rural SMEs

2. Literature Review

Cybersecurity resilience has become an essential concern for organizations globally, particularly for small and medium-sized enterprises (SMEs) in rural settings that are integral to critical infrastructure. National economies rely heavily on critical infrastructure sectors such as agriculture, energy, transportation, and healthcare. However, rural SMEs are generally more vulnerable due to limited cybersecurity resources, expertise, and overall under-resourcing. The reviewed literature explores existing studies on the vulnerabilities of rural SMEs, the role of cybersecurity resilience, and approaches focused on enhancing the cybersecurity posture of these businesses within critical infrastructure supply chains.

2.1. Weaknesses of rural SMEs within critical infrastructure supply chains

Rural SMEs involved in critical infrastructure supply chains encounter numerous difficulties in establishing robust digital security. These challenges include limited access to cybersecurity materials, inconsistent security standards, and insufficient cybersecurity awareness. Research indicates that rural SMEs are highly susceptible to cyberattacks due to their reliance on outdated technologies, lack of in-house specialists, and insufficient funds to implement effective cybersecurity measures.

2.1.1. Resource limitations and technological gap

Rural SMEs often lack the financial and technical capacities to adopt advanced cybersecurity tools. Parker et al. (2020) highlight the common issue of inadequate funding for cybersecurity investments among businesses in rural areas. Consequently, these SMEs frequently employ rudimentary security methods that are ineffective against sophisticated cyberattacks like ransomware and advanced persistent threats (APTs). This lack of resources contributes to the inherent weaknesses of rural SMEs, making them attractive targets for cybercriminals.

2.1.2. Inadequate cybersecurity expertise

Another significant impediment for rural SMEs is the scarcity of cybersecurity expertise. Harris and Jones (2019) propose that geographical isolation hinders these businesses from recruiting and retaining skilled IT talent. Most rural SMEs tend to manage cybersecurity independently due to the absence of local talent, often resulting in substandard security practices. This lack of specialized knowledge significantly elevates their risk to cyber threats. Moreover, many SMEs do not prioritize cybersecurity, a problem exacerbated by their limited understanding of the potential impacts of cyberattacks on their operations.

2.1.3. Cybersecurity training

Cybersecurity training is crucial for building resilience in SMEs. However, providing rural workers with the knowledge to identify and respond to cyber threats is not a common practice in many rural businesses. According to Smith et al. (2021), insufficient training leads to human error, such as clicking on phishing links or inadvertently downloading malicious software, thereby increasing the probability of successful cyberattacks. Regular training can significantly mitigate the susceptibility of rural SMEs to cyberattacks and their potentially immense effects.

2.2. Cybersecurity resilience: The importance to rural SMEs

Cybersecurity resilience is an organization's capability to respond and recover from a cyber-incident, ensuring the continuous operation of the organization despite an attack. Resilience is particularly vital for rural SMEs that play a critical role in essential infrastructure, as cyber disruptions can have far-reaching consequences across the entire supply chain. Brown and Adams (2020) emphasize that resilience encompasses not only preventing cyberattacks but also preparing for, responding to, and recovering from them.

2.2.1. Operational continuity

Rural SMEs are integral to sectors like agriculture, energy, and healthcare, where any failure can trigger disruptions in essential services. Mitchell et al. (2018) note that if rural SMEs handling sensitive data cannot recover quickly from a cyber-incident, it can cause cascading effects throughout entire supply chains. This makes them targets for adversaries seeking to maximize disruption. For instance, a cyberattack on a rural agricultural SME could disrupt the food supply chain, leading to shortages and economic instability.

2.2.2. Proactive risk management

Effective cybersecurity resilience is characterized by proactive risk management, which involves identifying existing vulnerabilities and establishing countermeasures. According to Miller (2020), frameworks promoting proactivity among rural SMEs regarding cybersecurity should focus on preventing, detecting, and rapidly responding to cybersecurity incidents. Such measures can help businesses reduce financial losses and operational downtime caused by cyberattacks.

2.2.3. Crisis action plans and recovery

It is crucial for rural SMEs to develop a culture of preparedness. Khan and Ahmed (2021) observe that most rural SMEs lack formal incident scenarios to guide them in effectively handling cyber incidents. Well-defined and organized incident response and recovery plans enable SMEs to maintain business operations and recover expeditiously in the event of a cyberattack, facilitating service restoration and data recovery.

2.3. Existing cybersecurity frameworks and models

Various cybersecurity frameworks have been established to guide organizations in building resilience. However, many of these frameworks are complex or demand resources that rural SMEs cannot realistically provide. Therefore, there is a necessity for scalable, affordable framework models that can effectively meet the specific needs of individual SMEs within the critical infrastructure supply chain in rural areas.

2.3.1. NIST Cybersecurity Framework (CSF)

The NIST Cybersecurity Framework is a widely accepted system for enhancing cybersecurity resilience across industries. The NIST framework comprises five core functions: Identify, Protect, Detect, Respond, and Recover. Brown and Adams (2020) highlight the framework's flexibility for SMEs of any size, offering a straightforward and comprehensive guide to addressing cybersecurity threats. Nevertheless, the NIST framework might be too extensive for rural SMEs to implement fully. Instead, a more focused and streamlined approach, concentrating on the most critical areas of cybersecurity resilience, could be more beneficial.

2.3.2. ISO/IEC 27001

The ISO/IEC 27001 standard for Information Security Management Systems (ISMS) provides a comprehensive solution for managing sensitive data and cybersecurity threats. Jones and Harris (2021) revealed that while this framework is commonly adopted by larger businesses, a simplified version could benefit rural SMEs. The standard's emphasis on risk management and continuous improvement makes it an ideal paradigm for organizations aiming to enhance their cybersecurity posture. However, it also requires significant resources, which may prove unfeasible for rural SMEs without more adaptable implementations.

2.3.3. Cybersecurity Framework for Critical Infrastructure (CF-CI)

The CF-CI framework aims to boost the cybersecurity resilience of organizations in critical infrastructure sectors, including energy, transportation, and healthcare. According to Miller (2020), the CF-CI framework is highly applicable to rural SMEs integrated into such sectors. This model promotes cooperation between smaller and larger organizations within the supply chain, facilitating the exchange of resources, tools, and threat intelligence. The CF-CI framework enables rural SMEs to overcome their cybersecurity weaknesses through shared responsibility and collective defense mechanisms.

2.3.4. Cyber resilience planning models

Cyber resilience planning models, such as the "Resilience by Design" methodology proposed by Mitchell et al. (2018), emphasize a proactive approach to cybersecurity. These models argue that a strong defense mechanism alone is insufficient for achieving resilience; they must include elements such as consistent monitoring, intelligence sharing, and effective response capabilities. Such models encourage cross-industry collaborations among SMEs to share resources, technologies, and establish best practices.

2.4. The importance of critical infrastructure to cybersecurity resiliency

Rural SMEs often operate within the supply chains of larger, critical infrastructure systems. Their cybersecurity resilience, as a component of these supply chains, becomes a crucial determinant for the overall stability of the infrastructure they support. Fletcher et al. (2019) emphasize that SMEs integrated into critical infrastructure sectors act as key nodes; if their operations are impaired, the effect can spread across the entire supply chain, disrupting services and causing widespread economic repercussions.

2.4.1. Supply chain vulnerability

A cyberattack on a rural SME can cause a domino effect, compromising the entire supply chain. Khan and Ahmed (2021) assert that cyber threats are increasingly targeting supply chains, where the weakness of a single company can lead to massive disruptions. They cite instances where cyberattacks on SME suppliers to larger organizations have resulted in significant data loss, financial losses, and operational paralysis. This underscores the necessity for resilient cybersecurity practices at all levels of the supply chain, including rural SMEs.

2.4.2. The value of teamwork and risk handling

Another recurring theme in the literature is the necessity for collaboration and shared risk management within critical infrastructure supply chains. Baker et al. (2020) state that it is vital for SMEs, especially those in rural environments, to forge collaborations with larger organizations, government agencies, and relevant business sectors to acquire cybersecurity resources and intelligence. Such partnerships can help rural SMEs stay abreast of emerging threats, adopt best practices, and improve their overall security posture. By engaging in cooperative cybersecurity initiatives, rural SMEs can contribute to the overall resilience of the critical infrastructure supply chains in which they participate.

2.5. New technologies and cyber capabilities

With the evolution of cyber threats, emerging technologies and innovations are being explored to enhance the cybersecurity capabilities of SMEs. Specifically, advancements in machine learning (ML), artificial intelligence (AI), and blockchain are being developed, as these technologies promise to improve the detection, response, and recovery abilities of rural SMEs.

2.5.1. AI and machine learning in threat detection

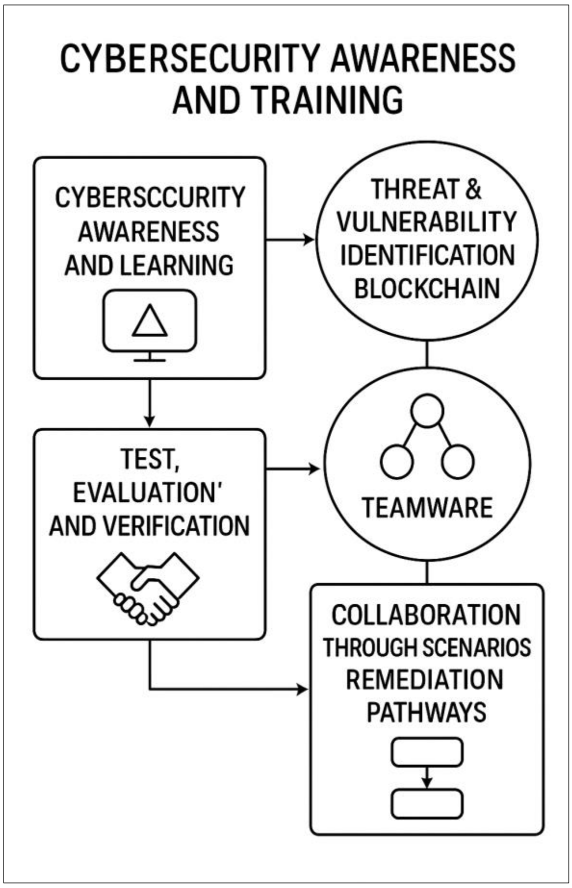
Machine learning and AI technologies have transformed the detection and combat of cybersecurity threats. According to Lee et al. (2021), these technologies help organizations identify patterns and anomalies that would otherwise remain undetected, enabling quicker responses to threats. For rural-based SMEs, integrating AI-based solutions can compensate for insufficient cybersecurity expertise by automating threat detection, analysis, and response.

2.5.2. Blockchain in supply chain security

Blockchain technology offers a transparent, secure, and decentralized method for tracing transactions and data exchange throughout supply chains. Chang and Ng (2020) noted that blockchain can also be applied to information security within critical infrastructure supply chains by creating an immutable record of transactions that cannot be altered or subjected to cyberattack. Blockchain may prove to be an effective technology for rural SMEs to verify the security and traceability of their activities within the supply chain system.

Rural SMEs are integral to critical infrastructure supply chains, yet they remain highly susceptible to cyberattacks due to limited financial resources and technical skills required to adopt sophisticated cybersecurity technology. The literature consistently demonstrates a growing interest in strengthening the cybersecurity resilience of such enterprises and emphasizes frameworks, strategies, and technologies that can be utilized to reduce these risks. Key insights from the literature highlight the necessity of customized strategies that account for the specific obstacles encountered by rural SMEs, the significance of collective management and risk sharing, and the judicious use of emerging technologies to enhance resilience.

The resilience of rural SMEs in the face of cyberattacks is crucial not only for their survival but also for the effectiveness and overall resilience of the critical infrastructure supply chain. The subsequent sections will detail how these components connect and underscore the importance of awareness, partnerships, and technology in establishing an effective defense against cyber threats for rural SMEs.


CYBERSECURITY AWARENESS AND TRAINING

CYBERSCCURITY AWARENESS AND LEARNING

THREAT & VULNERABILITY IDENTIFICATION BLOCKCHAIN

TEST, EVALUATION' AND VERIFICATION

TEAMWARE

COLLABORATION THROUGH SCENARIOS REMEDIATION PATHWAYS

Figure 2 Elements of a Cybersecurity Resilience Model to Rural SMEs

3. Material and Methods

This section outlines the materials and methods used to design and implement a cybersecurity resilience framework for underserved small and medium-sized enterprises (SMEs) in rural areas that are part of critical infrastructure supply chains. The framework aims to enhance these businesses' capabilities to detect, react to, and recover from cyber incidents, ensuring minimal disruption to their most critical activities. The development process was systematic, involving a comprehensive literature review, stakeholder analysis, adaptation of existing cybersecurity frameworks, integration of emerging technologies, and the creation of practical tools and strategies. The goal was to produce a scalable and cost-effective model tailored to the specific needs and constraints of these rural SMEs.

3.1. Literature review and gap analysis

The framework's development began with a comprehensive literature review focusing on cybersecurity resilience in SMEs, particularly those in rural areas. This review highlighted major challenges faced by rural SMEs, including limited resources, insufficient cybersecurity expertise, and low cybersecurity awareness. The review also examined current frameworks such as the NIST Cybersecurity Framework (CSF), ISO/IEC 27001, and industry-specific models like the Cybersecurity Framework for Critical Infrastructure (CF-CI).

The literature review identified significant gaps in existing research and frameworks. Most current models were either too complex for resource-constrained small businesses or did not specifically address the unique context of rural SMEs within critical infrastructure. This gap analysis informed the development of a streamlined and flexible framework, making it applicable and practical for rural SMEs in essential sectors like agriculture, energy, and healthcare.

3.2. Stakeholder analysis

The second step involved a comprehensive stakeholder analysis to identify key participants in the cybersecurity resilience framework. This analysis considered rural SMEs in critical infrastructure industries, alongside other relevant stakeholders such as government representatives, industry bodies, and larger companies supporting SME activities.

The key stakeholders identified are as follows:

- **Rural SMEs:** The primary target group for the framework, comprising small and medium-sized businesses operating within national essential infrastructure sectors, including agriculture, energy, and transport.
- **Government Agencies:** Federal, state, and local government bodies responsible for providing funding, policy guidance, and cybersecurity services to SMEs.
- **Cybersecurity Providers:** External or third-party providers offering cybersecurity services, training, and consultation.
- **Industry Associations:** Organizations representing specific sectors (e.g., agriculture, energy) that can advocate for and provide resources to rural SMEs.
- **Larger Enterprises:** Major companies whose supply chains include rural SMEs, capable of collaborating to enhance cybersecurity across the entire supply chain.

This stakeholder analysis provided a comprehensive understanding of each group's roles and responsibilities. It was also instrumental in identifying potential opportunities for cooperation and resource sharing, particularly in offering cybersecurity support and training to rural SMEs.

3.3. Framework design and adaptation

Following the literature review and stakeholder analysis, a specific cybersecurity resilience framework was designed. This framework is open, scalable, and readily applicable by rural SMEs within critical infrastructure supply chains. It builds upon established models like NIST and ISO/IEC 27001 but simplifies their provisions to align with the needs and capabilities of rural SMEs.

The most important elements of the framework are as follows:

- **Cybersecurity Awareness and Training:** This element focuses on educating rural SME employees regarding common security threats and best practices for internet use. It includes regular training on preventing phishing attacks, maintaining strong passwords, and secure Browse habits.

- **Risk Assessment and Management:** This procedure guides SMEs in identifying and evaluating cybersecurity risks specific to their operations. This element provides SMEs with tools and templates to perform vulnerability assessments and pinpoint necessary risk reduction actions.
- **Technology Adoption and Integration:** This component suggests cost-effective and easily implementable cybersecurity technologies for rural SMEs, including firewalls, antivirus programs, encryption, and multi-factor authentication (MFA) devices. The framework also proposes incorporating emerging technologies like artificial intelligence (AI) and machine learning (ML) to automate threat detection and response.
- **Incident Response and Recovery Plans:** This section offers guidelines for SMEs to develop clear plans outlining actions to undertake in the event of a cyberattack. This aspect also emphasizes the importance of data backup and recovery to ensure business continuity.
- **Risk Control and Partnership:** Rural SMEs are encouraged to cooperate with larger businesses, government organizations, and industry groups to exchange threat intelligence, resources, and best practices. This collaborative strategy aids in enhancing cybersecurity throughout the supply chain.

The framework's modular design allows rural SMEs to adopt individual components based on their specific needs, available resources, and risk profile. It also provides a step-by-step procedure to facilitate implementation, even for firms lacking extensive technical skills.

3.4. Incorporation of new technology

To ensure the framework remains effective in an evolving cyber threat landscape, new technologies are incorporated into the model. Technologies such as artificial intelligence (AI), machine learning (ML), and blockchain are particularly beneficial for rural SMEs, as they can automate threat detection, enhance response speed, and secure data transmission within supply chains.

3.4.1. Threat detection through artificial intelligence and machine learning

AI and ML technologies can be utilized to detect unusual patterns and potential cyberattack threats within an SME's network. The strength of these technologies lies in their ability to offer real-time detection, enabling faster identification and mitigation of threats before they escalate. Lee et al. (2021) highlight the potential of these technologies to automate threat detection and significantly increase overall resilience.

3.4.2. Blockchain for supply chain security

Blockchain technology provides a decentralized, secure, and transparent method for monitoring transactions and data exchange throughout a supply chain. According to Chang and Ng (2020), blockchain's capacity to create immutable records makes it an ideal tool for safeguarding the integrity of essential information in rural SME supply chains. The framework suggests applying blockchain to ensure transaction and data exchange security, especially for SMEs involved in multi-tier supply chains.

3.5. Data collection and data analysis

To determine the viability of the cybersecurity resilience framework, data was collected from a sample of rural SMEs willing to implement the framework. Data collection methods included surveys, cybersecurity assessments, and interviews. The aim was to analyze the existing cybersecurity measures in these SMEs, identify their weakest areas, and assess their readiness to adopt the proposed framework.

3.5.1. Instruments of data collection

- **Surveys:** A well-designed questionnaire was employed to gather quantitative information regarding the state of cybersecurity in rural SMEs. Questions focused on themes such as cybersecurity awareness, technology adoption, risk management procedures, and incident response capabilities.
- **Interviews:** Semi-structured interviews were conducted with business owners and key staff members to obtain qualitative data on their current cybersecurity challenges and the tools or practices needed to build enhanced resilience to cyberattacks.
- **Cybersecurity Assessments:** SMEs were requested to undergo a self-assessment tool to gain an overview of their security environment and potential areas of vulnerability.

3.5.2. Data analysis

Both qualitative and quantitative methods were applied to the collected data. Descriptive statistics were used to identify trends and patterns related to cybersecurity practices, while thematic analysis helped uncover major directions and impediments to cybersecurity measure implementation. The findings from this analysis were used to refine the framework, tailoring it to the specific requirements of rural SMEs.

3.6. Pilot implementation and evaluation

A pilot application of the cybersecurity resilience framework was conducted with a selected group of rural SMEs. The objective of the pilot trial was to determine the framework's feasibility and effectiveness in a real-world context. Participating SMEs were provided access to the entire framework, including training materials, risk assessment systems, and incident response templates.

3.6.1. Evaluation criteria

The effectiveness of the pilot implementation was determined using the following criteria:

- **Enhancement of Cybersecurity Knowledge:** Changes in cybersecurity awareness among SME employees were assessed through pre- and post-implementation surveys.
- **Adoption of Cybersecurity Technologies:** The extent to which SMEs adopted new technologies (e.g., firewalls, antivirus programs, MFA) was measured.
- **Incident Response and Recovery:** SMEs were tested on their response to and recovery from simulated cyberattacks, including their adherence to incident response plans.
- **Business Continuity:** The framework's impact on business continuity during and after simulated cyberattacks was assessed through evaluations of downtime and recovery time.

The approach to developing and accessing the cybersecurity resilience framework for rural SMEs within critical infrastructure supply chains involved a critical literature review, analysis of stakeholder input, adaptation of existing frameworks, and incorporation of new emerging technologies. The outcomes of the initial pilot implementation and evaluation will guide the final version of the framework, ensuring it is realistic, scalable, and sustainable in fostering resilient cybersecurity for rural SMEs. The subsequent section will provide an overview of the framework's crucial aspects and associated goals.

Table 2 The Major Elements of Cybersecurity Resilience Framework to Rural SMEs

Component	Goal	Implementation Method
The Awareness and Training on Cybersecurity Awareness and Training	Train the staff on cybersecurity threats and how to do it.	Governance trainings, online classes, and awareness programs on a regular basis.
Risk assessment and Risk management	Develop and evaluate the uniquely SME cybersecurity risks.	Assessment of risk can be done by means of risk assessment tools and templates to assess vulnerabilities.
Technology Adoption and integration	Install low cost security measures that can scale well to ensure protection.	Install firewalls, antivirus, encryptions and multi factor authentication.
Incident response and recovery Branch	Decide on and put in place a well-procedural architecture to break and heal the effects of cyber-attacks.	Develop and do the incident response and disaster recovery exercises.
Teamwork and Co-Managed risk deals with	Encourage the cooperation of larger organizations and government agencies to avail resources.	Enter cooperation and exchange information on threats.

4. Research and Methodology: A Cybersecurity Resilience Framework for Underserved Rural SMEs within Critical Infrastructure Supply Chains

This section describes the methodology employed to design a cybersecurity resilience framework for underserved rural Small and Medium-sized Enterprises (SMEs) within critical infrastructure supply chains. Such rural businesses are crucial for the smooth operation of various sectors, including agriculture, energy, healthcare, and transportation, but they face distinct challenges in defending against cyberattacks. This study implements a mixed-methods approach, combining qualitative and quantitative research strategies to understand the issues affecting rural SMEs and to design an effective cybersecurity resilience framework. The research design encompasses a comprehensive literature review, stakeholder analysis, development and modification of cybersecurity frameworks, and a pilot program with rural SMEs to evaluate the proposed framework's effectiveness.

4.1. Research method, approach, and design

The study's objectives are to identify the cybersecurity vulnerabilities of rural SMEs within critical infrastructure supply chains and to formulate a comprehensive, scalable cybersecurity resilience strategy. The research methodology is structured into two phases: Exploratory Research (Phase 1) and Practical Implementation and Evaluation (Phase 2).

4.1.1. Phase 1: Exploratory research

The initial stage of the research involves compiling preliminary knowledge through a literature review, identifying relevant stakeholders, and developing a preliminary cybersecurity framework. This step is essential for understanding the unique problems faced by rural SMEs and forming the foundation for the resilience framework's development. The major steps undertaken during this phase include:

- **Literature Review:** An in-depth analysis of academic and industry literature on cybersecurity resilience, specifically focusing on SMEs in rural areas. The review addresses common vulnerabilities, challenges, and existing frameworks for enhancing cybersecurity robustness. Key topics include:
  - Vulnerabilities of rural SMEs within critical infrastructure supply chains.
  - Inhibitors to cybersecurity, such as resource limitations and inadequate skills.
  - Relevant cybersecurity paradigms like the NIST Cybersecurity Framework, ISO/IEC 27001, and the Cybersecurity Framework for Critical Infrastructure.
  - The role of emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), and blockchain in promoting resilience.
- **Stakeholder Analysis:** Identifying key stakeholders who will contribute to enhancing the cybersecurity posture of rural SMEs. This includes rural SME owners, government agencies, cybersecurity service providers, industry associations, and larger enterprises willing to collaborate on supply chain security. The stakeholder analysis aims to understand each group's roles, responsibilities, and potential contributions to enhancing cybersecurity resilience.
- **Development of a Cybersecurity Resilience Framework:** Based on the literature review and stakeholder insights, a cybersecurity resilience framework for rural SMEs is developed. This framework is designed to be simple, scalable, cost-efficient, adaptable, and practical for implementation. It integrates concepts from existing frameworks but simplifies them to suit the specific needs and capabilities of rural SMEs.

4.1.2. Phase 2: Implementation and evaluation

The second stage of the study focuses on testing and evaluating the cybersecurity resilience framework by implementing it in a sample of rural SMEs. This phase involves the following steps:

- **Pilot Program Implementation:** The framework is piloted with a group of rural SMEs willing to participate. These enterprises are selected based on their involvement in critical supply chain services and their willingness to implement the framework. The framework is implemented in these businesses through a combination of training, assessments, and technology introduction.
- **Data Collection:** Data collection is performed using three primary methods:
  - **Surveys:** A structured questionnaire is administered to SME owners, managers, and employees to assess their current cybersecurity practices and awareness of cyber threats. Surveys are designed to generate quantitative data on areas such as cybersecurity tool usage, training and risk management processes, and cybersecurity risk awareness.

  - **Interviews:** Semi-structured interviews are conducted with relevant SME staff to obtain qualitative information. Interviews aim to explore specific business characteristics, challenges related to framework implementation, and the perceived effects on their cybersecurity posture.
  - **Cybersecurity Assessments:** SMEs are requested to complete a cybersecurity self-assessment tool to establish a baseline understanding of their security environment and potential vulnerabilities. These self-assessments serve as baseline data for measuring the framework's effectiveness post-implementation.
- **Evaluation:** The success of the pilot program is analyzed according to several criteria:
  - **Enhancement of Cybersecurity Awareness:** Measured by comparing the framework's impact on staff understanding and knowledge of cybersecurity issues before and after implementation.
  - **Adoption of Cybersecurity Tools:** Assessed by the level at which SMEs incorporate simple cybersecurity solutions, including firewalls, antivirus programs, encryption, and multi-factor authentication (MFA).
  - **Incident Response and Recovery:** Evaluated by the SMEs' capability to respond to and recover from simulated cyberattacks. This is determined by gauging the efficiency of incident response plans, data backup procedures, and recovery performance.
  - **Business Continuity:** The framework's impact on business continuity is determined by comparing downtime and operational disruptions before and after its implementation.

4.2. Research methods

The study employs a **mixed-methods approach**, integrating both qualitative and quantitative data collection methods to obtain a comprehensive understanding of cybersecurity challenges and the effectiveness of the proposed framework in rural SMEs.

4.2.1. Qualitative methods

- **Interviews:** Semi-structured interviews are conducted with key stakeholders, including SME owners, managers, and employees. These interviews provide a deeper analysis of their cybersecurity problems, how these issues impact their business operations, and the specific needs of rural SMEs in critical infrastructure supply chains. External experts, such as cybersecurity service providers and government representatives, are also interviewed to gather their perspectives on the framework's potential and identify collaboration opportunities.
- **Focus Groups:** Focus groups are convened with representatives from SMEs that have implemented the framework. These sessions facilitate discussion about the challenges and successes encountered during implementation. Focus groups allow for sharing experiences, identifying common issues, and gathering feedback on the framework's versatility and usability.

4.2.2. Quantitative methods

- **Surveys:** Surveys collect information from a larger sample of SMEs regarding their current cybersecurity practices, knowledge, and preparedness. The surveys aim to quantify the cybersecurity posture of SMEs both before and after the framework's implementation. Key areas of interest include:
  - SME staff knowledge and training levels related to cybersecurity.
  - Employment of cybersecurity tools and technologies.
  - Effectiveness of current incident response plans.
  - Impact of the cybersecurity framework on business operations.
- **Cybersecurity Self-Assessments:** This tool is provided to SMEs to review their cybersecurity status. It offers a checklist of best practices and security measures, assisting SMEs in identifying areas of vulnerability. The outcomes of these assessments are compared to monitor improvements following the framework's application.

4.3. Data analysis

Data analysis in this study integrates both qualitative and quantitative approaches.

4.3.1. Qualitative data analysis

Data collected from interviews and focus groups are transcribed and analyzed using **thematic analysis**. Thematic analysis is employed to identify recurrent themes, patterns, and insights gleaned from the qualitative information. This analysis aims to understand SMEs' experiences, their cybersecurity challenges, and ways to refine the framework.

4.3.2. Quantitative data analysis

Quantitative data from surveys are analyzed using **statistical analysis**, including descriptive statistics and comparative analyses (e.g., pre- and post-implementation comparisons). Quantitative data acquired during the cybersecurity self-assessments are also evaluated to determine the extent to which the framework has positively impacted the SMEs' cybersecurity postures.

4.4. Ethical considerations

Ethical conduct is rigorously observed throughout the research to guarantee the **anonymity and privacy** of all respondents. All SME owners, managers, and employees provide informed consent prior to data collection. Participants are reassured that their answers will remain anonymous and will only be used for research purposes. The study also ensures that any confidential business information provided by the SMEs remains strictly confidential.

The research methodology employed in this study utilizes rigorous qualitative and quantitative methods to develop an in-depth understanding of the cybersecurity vulnerabilities of rural SMEs within critical infrastructure supply chains. The mixed-methods design ensures that both the lived experiences and the statistical impact of the cybersecurity resilience framework are comprehensively captured. By conducting thorough literature reviews, stakeholder analysis, and a well-designed pilot experiment, this research aims to offer a practical, cost-effective, and scalable framework that can significantly improve the cybersecurity posture of underserved rural SMEs, ultimately supporting the continued operation of essential infrastructure. The findings of this study will inform the final model development and provide valuable suggestions for enhancing cybersecurity resilience among rural SMEs

5. Conclusion

This research highlights the urgent need to address the importance of cybersecurity resilience among underserved rural SMEs, particularly those within critical infrastructure supply chains. These enterprises are crucial in vital sectors such as agriculture, energy, transportation, and healthcare; however, their cybersecurity weaknesses pose significant threats to the stability and survival of critical infrastructures. The proposed study aims to identify the main issues rural SMEs experience, employing a mixed-methods research approach.

The designed cybersecurity resilience framework, formulated after an extensive literature review, stakeholder examination, and pilot implementation, offers a unique, scalable, and affordable approach to dealing with these issues. This framework provides a practical guide to achieving better cybersecurity in rural SMEs by adapting elements from well-established models such as NIST and ISO/IEC 27001 and simplifying this information to suit the particular needs of SMEs in such regions.

The pilot phase demonstrated that SMEs could significantly enhance their cybersecurity posture by employing a well-organized strategy that includes cybersecurity training, risk analysis, the application of low-cost technologies, and the preparation of incident response and recovery strategies. The framework also emphasizes collaboration among rural SMEs, larger businesses, government, and industry associations to encourage shared risk management and enhance collective defense.

Finally, the study argues for the relevance of establishing cybersecurity resilience at all levels of the supply chain to guarantee the long-term stability of critical infrastructure. The results of this study are an important contribution to policymakers, industry leaders, and the SMEs themselves as they seek ways to reduce cyber risks and ensure that key sectors in rural areas continue to operate. The developed framework will be utilized by rural SMEs as a key tool to boost their cybersecurity procedures, enabling them to respond effectively to attackers and ensure operational continuity even when subjected to an attack.

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