# Governance of Cyber and Environmental Risks in Algerian Food Security

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**Abstract:**
Algeria faces a multifaceted challenge in securing its national food system, situated at the intersection of environmental stressors and emerging cyber threats. Traditionally, food security assessments have focused primarily on production and consumption dynamics; however, contemporary risks extend beyond physical resources to encompass digital vulnerabilities and governance complexities. This study explores how environmental pressures, including water scarcity, climate variability, and desertification, interact with cybersecurity threats targeting critical agricultural and logistical infrastructures, forming a compound risk environment. By adopting an integrated risk governance framework, this research examines the readiness of Algeria's food systems to absorb shocks, maintain operational continuity, and ensure sustainable access to safe and nutritious food for its population. The study employs a descriptive analytical approach, drawing on national production statistics, supply chain analyses, and regulatory frameworks, to illustrate the interdependencies between environmental and cyber dimensions. The findings highlight critical gaps in digital resilience, institutional coordination, and strategic integration, revealing that existing policies inadequately address the intersection of technological, ecological, and geopolitical vulnerabilities. Ultimately, this research argues for a proactive governance model that aligns environmental adaptation strategies with cybersecurity measures, strengthening both physical and digital sovereignty over agricultural resources. By framing food security through a lens of complex risk interaction, this study provides actionable insights for policymakers, demonstrating how integrated governance mechanisms can enhance Algeria's capacity to anticipate, mitigate, and respond to simultaneous environmental and cyber threats, thereby safeguarding national resilience and long-term food stability.
**Keywords:** Algeria Food Security, Environmental Risks, Cybersecurity in Agriculture, Water Scarcity, Digital Resilience, Integrated Risk Governance.

**Introduction:**

Ensuring food security in Algeria has evolved into a strategic priority, shaped not only by domestic agricultural productivity but also by complex interactions between environmental, technological, and geopolitical factors. Historically, a simple balance of production and consumption often measured food security; however, the modern landscape requires a far more nuanced understanding. Environmental pressures, particularly water scarcity, drought, and land degradation, increasingly threaten Algeria's agricultural outputs, while the digitization of agricultural operations introduces new vulnerabilities that, if exploited, could destabilize entire supply chains. The rise of Agriculture 4.0 technologies, including automated irrigation, precision farming, and IoT-enabled monitoring, has enhanced efficiency and productivity but simultaneously created critical points of cyber vulnerability. Attacks on digital infrastructure can disrupt supply chains, compromise data integrity, and impair real-time resource management, amplifying the impact of natural shocks. Furthermore, Algeria's geopolitical positioning adds an additional layer of complexity. Heavy reliance on grain imports, coupled with shifting global trade patterns and diplomatic tensions, exposes the country to external supply risks, which are magnified by domestic environmental and cyber challenges.

This study centers on the question: to what extent can Algeria's national food security system withstand the compounded risks of environmental stress and cyber threats, while maintaining resilience amid global uncertainty? Addressing this question requires a multi-dimensional perspective that goes beyond conventional production-based analyses. The research adopts a conceptual framework that integrates environmental resilience and digital security as mutually reinforcing components of food system governance. Environmental resilience encompasses water management strategies, climate adaptation practices, and the mitigation of resource scarcity impacts on agricultural production. Cybersecurity measures, on the other hand, focus on protecting digital platforms, automated systems, and supply chain networks from unauthorized access, disruption, or data manipulation. By examining the intersection of these domains, the study seeks to provide a holistic understanding of the vulnerabilities and opportunities inherent in Algeria's food system.

The approach taken in this research is descriptive and analytical, combining quantitative data on production, consumption, and import dependency with a qualitative assessment of regulatory frameworks and technological infrastructure. This methodology enables a detailed evaluation of both systemic vulnerabilities and potential resilience-building strategies. Preliminary analyses indicate that while Algeria has made strides in modernizing agricultural technologies and implementing sector-specific digital protections, significant gaps remain in integrating environmental and cyber risk management, particularly in institutional coordination, policy alignment, and operational preparedness. The study aims to provide actionable insights for policymakers, suggesting that strengthening food system resilience requires an integrated governance model that simultaneously addresses environmental adaptation, digital security, and strategic decision-making. In doing so, Algeria can develop a robust framework capable of anticipating compound risks, mitigating disruptions, and ensuring the continuity of safe and adequate food supplies for its population.

## 1. Theoretical Framework

### 1.1 Understanding Food Security in the Contemporary Context

Food security has long been recognized as a fundamental pillar of national stability, economic development, and human well-being. Traditionally, the concept was associated with the ability of a country to ensure adequate food production and maintain sufficient supplies to meet the nutritional needs of its population. Over time, however, the concept has evolved significantly due to profound transformations in global economic systems, environmental conditions, and technological developments. Today, food security is no longer limited to agricultural output or import capacity; it encompasses a complex set of interrelated dimensions involving accessibility, quality, stability, sustainability, and resilience. Recent scholarship highlights that these dimensions are particularly vulnerable in nations where internal agricultural potential remains underutilized, necessitating a shift from import-heavy models toward systemic domestic resilience (Bouziane et al., 2024).

The contemporary understanding of food security emphasizes the capacity of individuals and communities to obtain sufficient, safe, and nutritious food at all times. This perspective recognizes that food insecurity can emerge even when food is physically available. Economic inequality, supply chain disruptions, political instability, environmental degradation, and technological failures may all prevent populations from accessing essential food resources. Consequently, modern food security studies increasingly adopt multidimensional frameworks that account for both physical and systemic vulnerabilities.

The acceleration of globalization has further transformed the nature of food security challenges. National food systems are now deeply interconnected with international trade networks, logistics infrastructures, financial markets, and digital technologies. While these connections create opportunities for efficiency and productivity, they also expose countries to external shocks beyond their direct control. Global crises such as pandemics, geopolitical conflicts, and supply chain disruptions have demonstrated how vulnerabilities in one region can rapidly affect food availability and prices elsewhere.

For Algeria, food security occupies a particularly strategic position due to the country's demographic growth, climatic constraints, and dependence on imported cereals. Ensuring food security requires not only increasing agricultural production but also strengthening the resilience of the entire food system. This includes securing water resources, modernizing agricultural practices, improving logistical infrastructures, and protecting critical digital systems that increasingly support food production and distribution. Therefore, food security must be viewed as a dynamic and integrated system where environmental, technological, economic, and political factors continuously interact.

The growing complexity of these interactions has given rise to new conceptual approaches that place resilience at the center of food security governance. Rather than focusing solely on preventing crises, resilience-based approaches seek to enhance the ability of food systems to anticipate, absorb, adapt to, and recover from disruptions. Within this framework, environmental sustainability and cybersecurity emerge as two critical components that must be managed simultaneously to ensure long-term food stability. This transition necessitates reconciling the inherent limitations of a rentier economy with the imperative to foster private-sector innovation and technological integration (Inezarene & Intissar, 2024; Sabrina & Siham, 2025).

### 1.2 Environmental Risks and Food System Vulnerability

Environmental risks have become one of the most significant threats to food security worldwide. Climate change, water scarcity, desertification, soil degradation, and extreme weather events increasingly affect agricultural productivity and challenge the sustainability of food systems. These risks are particularly severe in regions characterized by arid and semi-arid climates, where agricultural production already operates under considerable environmental constraints.

Algeria represents a clear example of this reality. The country's geographical and climatic characteristics expose its agricultural sector to recurring droughts, irregular rainfall patterns, rising temperatures, and increasing pressure on water resources. Agriculture remains highly dependent on climatic conditions, making production levels vulnerable to environmental fluctuations. As climate variability intensifies, the reliability of agricultural outputs becomes increasingly uncertain, creating significant challenges for national food planning and strategic resource management.

Among the various environmental challenges facing Algeria, water scarcity stands out as the most critical. Water is the foundation of agricultural production, and any disruption in its availability directly affects crop yields and food supplies. Population growth, urban expansion, industrial demand, and climate change collectively increase competition for limited water resources. This situation forces policymakers to explore alternative solutions, including desalination, wastewater reuse, and more efficient irrigation technologies. However, current governance structures often prioritize supply-side expansion over structural efficiency, which frequently leads to the mismanagement of existing hydraulic potential (Bouchentouf & BENABDELI, 2021, p. 414).

Environmental risks extend beyond immediate production losses. They also affect infrastructure, rural livelihoods, and economic stability. Prolonged droughts can reduce farmers' incomes, increase rural migration, and contribute to social vulnerabilities. Simultaneously, environmental degradation may reduce the long-term productivity of agricultural land, creating structural challenges that persist even after climatic conditions improve.

The interconnected nature of environmental systems means that disruptions often generate cascading effects. Water shortages may lead to lower agricultural production, increased food imports, higher food prices, and greater exposure to external market fluctuations. These cascading consequences illustrate why environmental risks cannot be treated as isolated agricultural problems. Instead, they must be understood as strategic challenges affecting national security, economic resilience, and social stability. Furthermore, the degradation of natural resources and increasing desertification underscore the urgency of implementing comprehensive agrarian reforms to bolster ecosystem resilience (BENMEHAIA & Bédrani, 2025), (Habib et al., 2025, p. 270).

Addressing these risks requires a shift from reactive crisis management toward proactive environmental governance. Governments must invest in climate adaptation strategies, sustainable resource management, technological innovation, and institutional coordination. Building environmental resilience involves not only responding to current challenges but also preparing food systems to withstand future uncertainties. In this regard, environmental governance becomes a central component of broader food security strategies aimed at ensuring sustainable development and national resilience.

### 1.3 Cybersecurity and Critical Agricultural Infrastructure

The rapid digital transformation of agriculture has created new opportunities for improving productivity, efficiency, and resource management. Advanced technologies such as artificial intelligence, satellite monitoring, remote sensing, automated irrigation systems, cloud computing, and the Internet of Things are increasingly integrated into agricultural operations worldwide. These innovations support precision agriculture, optimize water use, improve crop monitoring, and enhance decision-making processes. However, they also introduce new forms of vulnerability that were largely absent from traditional food security discussions. The integration of interconnected digital systems into essential supply chain infrastructure creates a heightened risk profile, as malicious cyber-attacks targeting agricultural data or automated control networks can cause systemic disruptions to food distribution (Mehibel et al., 2025, p. 32).

As agricultural systems become more dependent on digital technologies, cybersecurity emerges as a critical component of food system resilience. Modern agricultural infrastructures rely on interconnected digital networks that collect, process, and transmit large volumes of information. These systems manage irrigation networks, storage facilities, transportation logistics, market information platforms, and supply chain operations. Any disruption affecting these digital infrastructures can have direct consequences on food production and distribution.

Cyber threats targeting critical infrastructures have increased significantly in recent years. Attacks involving ransomware, data theft, system manipulation, and operational disruption demonstrate the growing vulnerability of digitally connected sectors. Agricultural systems are particularly attractive targets because of their strategic importance and their increasing dependence on automated technologies. A successful cyberattack can interrupt production processes, compromise sensitive data, disrupt transportation networks, and create shortages within food supply chains. Moreover, the integration of precision agriculture tools—such as GPS-guided systems and autonomous machinery—has expanded the attack surface for potential sabotage, where compromised data streams could lead to large-scale failures in harvesting or planting operations (Grispos et al., 2025, p. 1; Gupta et al., 2026).

In Algeria, digital transformation initiatives are gradually expanding across the agricultural sector. Government programs promote the adoption of smart agriculture technologies, digital monitoring systems, and data-driven resource management tools. While these developments contribute to modernization objectives, they also create new security challenges that require dedicated attention. The protection of digital infrastructures must evolve alongside technological adoption to ensure that modernization efforts do not unintentionally increase systemic vulnerabilities. Consequently, policymakers must integrate cybersecurity frameworks into the broader national agricultural policy to proactively mitigate risks associated with the proliferation of these high-tech systems (Jones, 2025).

Cybersecurity challenges extend beyond technical considerations. They involve issues of governance, institutional capacity, legal frameworks, workforce training, and strategic planning. Effective cybersecurity requires coordination among public institutions, private sector actors, technology providers, and agricultural stakeholders. Without such coordination, isolated security measures may fail to address the interconnected nature of modern digital ecosystems.

The concept of cyber resilience has therefore become increasingly important. Cyber resilience goes beyond preventing attacks; it focuses on ensuring that systems can continue operating during disruptions and recover rapidly after incidents occur. In the context of food security, cyber resilience contributes directly to the continuity of agricultural production, supply chain operations, and resource management systems. It represents a fundamental element of national resilience in an era where digital infrastructures play an increasingly central role in sustaining critical sectors. Establishing this resilience necessitates the development of comprehensive mitigation frameworks that specifically address vulnerabilities within the Internet of Agricultural Things, including firmware-level security and the validation of blockchain-secured edge computing (Dzreke, 2025).

### 1.4 Integrated Risk Governance: Linking Environmental and Cyber Resilience

Traditional approaches to risk management often address threats separately, treating environmental risks, technological vulnerabilities, and geopolitical challenges as distinct policy domains. While this approach may simplify analysis, it fails to capture the complex interactions that characterize contemporary food systems. Modern risks are increasingly interconnected, creating situations where disruptions in one sector generate cascading consequences across multiple domains. This reality highlights the need for integrated risk governance frameworks capable of addressing complex and compound threats. Such frameworks must acknowledge the intersection between environmental resource management and digital stability, particularly where cyber-biosecurity threats to drinking water or energy grids directly jeopardize agricultural viability (Duncan et al., 2019, p. 5; Ododo & Sadiq, 2025).

Integrated risk governance is based on the recognition that environmental and cyber risks are not independent phenomena. Instead, they frequently interact and reinforce one another. Water management systems, for example, increasingly depend on digital technologies for monitoring, control, and operational decision-making. A cyberattack targeting water infrastructure during a period of severe drought could significantly amplify the consequences of environmental stress. Similarly, climate-related emergencies may create operational conditions that increase the vulnerability of digital systems to cyber exploitation.

The concept of complex risk provides a useful analytical framework for understanding these interactions. Complex risks emerge when multiple threats occur simultaneously or sequentially, generating consequences that exceed the impact of individual hazards. In such situations, traditional sectoral approaches become insufficient because they fail to address the dynamic relationships between interconnected systems. Food security represents a particularly relevant domain for applying this perspective due to its dependence on environmental resources, technological infrastructures, economic networks, and political institutions. Addressing these challenges requires a shift toward holistic governance models that account for the normative assumptions influencing how we manage food system vulnerabilities (Moragues-Faus et al., 2017, p. 187).

An integrated governance model seeks to strengthen resilience across all these dimensions simultaneously. It promotes coordination among environmental agencies, cybersecurity authorities, agricultural institutions, water management organizations, and strategic planning bodies. Such coordination improves information sharing, enhances early warning capabilities, and supports more effective responses to emerging threats.

For Algeria, adopting an integrated governance framework offers significant strategic advantages. Environmental pressures, water scarcity, technological modernization, and global market uncertainties are likely to remain defining features of the national food security landscape. Addressing these challenges requires policies that recognize their interdependence rather than treating them as isolated issues. By integrating environmental resilience with cybersecurity preparedness, Algeria can strengthen its capacity to anticipate disruptions, reduce systemic vulnerabilities, and ensure the continuity of critical food systems.

This integrated perspective forms the theoretical foundation of the present study. It provides a framework for analyzing how environmental and cyber risks interact within the Algerian context and how governance mechanisms can be designed to enhance overall food system resilience. By examining the systemic interdependencies within these domains, this research evaluates how cross-sectoral policy integration can mitigate the cascading vulnerabilities that threaten agricultural integrity (Hassen & Bilali, 2024, p. 10).

## 2. Food Security Challenges in Algeria

### 2.1 Agricultural Production and Domestic Constraints

Agriculture in Algeria remains a central pillar of national food security, yet the sector faces persistent structural and environmental challenges. Domestic production levels are insufficient to meet the needs of a rapidly growing population, particularly in staple crops such as wheat and barley. Agricultural output is heavily influenced by regional disparities, with the northern and highland regions accounting for the majority of arable land and crop production. In contrast, southern and desert regions have limited agricultural activity due to harsh climatic conditions and scarce water resources. This uneven distribution of agricultural capacity intensifies regional vulnerabilities and necessitates targeted interventions to enhance local productivity.

Several factors constrain domestic agricultural production in Algeria. First, climatic variability, including frequent droughts, irregular rainfall, and soil degradation, directly reduces crop yields. Second, traditional farming methods, limited mechanization, and inadequate adoption of modern agronomic practices hinder efficiency. Third, infrastructure challenges, such as poor irrigation networks, limited storage facilities, and inefficient transport systems, contribute to post-harvest losses and inefficiencies in the supply chain. Finally, resource scarcity, particularly water, places a structural limitation on scaling up agricultural production without significant investment in water management technologies and alternative irrigation solutions. Furthermore, empirical evidence underscores a positive correlation between cereal production and both precipitation levels and cultivated land area, suggesting that future expansion strategies must reconcile these environmental dependencies with the constraints imposed by rising greenhouse gas emissions (Katia, 2025).

Despite these challenges, Algeria has implemented programs aimed at improving agricultural productivity, such as the introduction of high-yield crop varieties, mechanization incentives, and investment in pilot smart farming projects. However, these initiatives remain fragmented, with limited integration across regions and insufficient alignment with broader national strategies. Consequently, Algeria continues to rely heavily on imported food products, creating strategic vulnerabilities that are exacerbated by international market fluctuations and geopolitical tensions. Strengthening domestic production capacity requires a holistic approach that addresses environmental constraints, technological modernization, and institutional coordination simultaneously, ensuring that the food system is resilient to both internal and external shocks. Beyond production constraints, optimizing land market efficiency through a meticulous evaluation of agrarian structures remains essential for transforming current agricultural potential into sustained output (Benmehaia & Bekkis, 2024).

### 2.2 Water Scarcity and Resource Management

Water scarcity is one of the most pressing environmental challenges affecting Algeria's food security. The country's arid and semi-arid climate results in limited freshwater availability, unevenly distributed across regions. Northern agricultural zones, where most intensive farming occurs, experience high water stress, while southern regions hold large groundwater reserves that are largely untapped due to technical, economic, and logistical constraints. This imbalance between water availability and agricultural demand creates persistent pressure on irrigation systems and limits the potential for sustainable expansion of crop production.

Algeria has pursued alternative strategies to address water scarcity, including investments in desalination plants, wastewater reuse, and the modernization of irrigation infrastructure. Desalination, in particular, represents a strategic response to acute water shortages in coastal areas. Large-scale plants have been commissioned to provide drinking water and support agricultural needs, yet these projects are energy-intensive and rely on complex technological systems. This dependence introduces both financial and operational risks, as any disruption in energy supply, technical failure, or cyberattack could compromise water availability for agricultural production and food processing. Furthermore, the high demand for fodder crops used in livestock production continues to deplete limited groundwater reserves, complicating efforts to achieve long-term food sovereignty (Suliman et al., 2024, p. 147).

The management of water resources in Algeria is also challenged by climate variability. Irregular rainfall patterns, rising temperatures, and desertification reduce surface water availability, making agriculture more reliant on groundwater extraction and engineered solutions. In parallel, competition among agricultural, industrial, and domestic users intensifies resource scarcity, requiring integrated water governance frameworks that prioritize efficiency, sustainability, and risk mitigation. Enhancing resilience in the agricultural sector thus depends not only on technological solutions but also on policy coordination, regulatory enforcement, and the strategic planning of water allocations in a context of environmental uncertainty. Recent studies indicate that adopting water-saving technologies is essential, although the current evidence base regarding their long-term efficacy under Algerian climatic conditions remains notably limited (Oulmane, 2019, p. 81).

### 2.3 Import Dependency and Geopolitical Exposure

Algeria's domestic production shortfalls necessitate significant reliance on imported food commodities, particularly cereals such as wheat. This dependence exposes the country to fluctuations in global markets, geopolitical tensions, and supply chain disruptions. The concentration of imports from a limited number of supplier countries magnifies the risk of disruption, as political instability, trade restrictions, or conflicts in exporting nations can directly impact Algeria's food supply.

Diversification of import sources has become a strategic priority to reduce vulnerability, yet this approach does not eliminate exposure to global shocks. Prices for imported grains are influenced by worldwide supply-demand dynamics, transportation costs, and currency fluctuations, which may increase food insecurity domestically. Additionally, global crises, such as climate-related crop failures or conflicts affecting major exporters, can rapidly escalate the risk of shortages and price spikes. Consequently, Algeria's national food security strategy must balance domestic production enhancement with proactive risk management for import dependency, including strategic reserves, contractual safeguards, and monitoring of international market trends. Furthermore, fostering regional cooperation—specifically through the exchange of water governance frameworks and climate-smart agricultural technologies with neighboring countries—could mitigate systemic risks and harmonize responses to shared environmental vulnerabilities (BENMEHAIA et al., 2025).

The geopolitical dimension further complicates food security governance. Algeria must navigate international trade relationships carefully to ensure consistent access to essential commodities while maintaining strategic autonomy. This requires not only economic planning but also alignment with cybersecurity and environmental governance frameworks, as disruptions in one domain can cascade into others. For instance, cyberattacks on port infrastructure or logistics platforms could impede the distribution of imported food, highlighting the interconnected nature of physical, digital, and geopolitical vulnerabilities.

**2.4 Interconnectedness of Risks: Environmental and Cyber Dimensions**

The convergence of environmental and cyber risks creates a complex threat landscape for Algeria's food security. Environmental stressors, such as drought and water scarcity, increase reliance on technological interventions like smart irrigation and desalination, which in turn are highly dependent on digital infrastructure. This interdependence introduces a "cyber-environmental" risk nexus, whereby disruptions in one system amplify vulnerabilities in another. A cyberattack on irrigation networks or water management platforms, for example, could significantly worsen the consequences of an existing drought, affecting crop yields, food availability, and regional stability. Moreover, the digitalization of national supply chains intended to optimize food distribution introduces latent systemic vulnerabilities, necessitating the integration of cybersecurity protocols within broader agricultural risk management frameworks (Daoudi & Bouzid, 2020; samia, 2026).

This interaction underscores the necessity of integrated risk governance. Policies and strategies must simultaneously address the management of environmental resources and the protection of digital systems to ensure systemic resilience. Isolated approaches, whether focused solely on agricultural production, water resource management, or cybersecurity, are insufficient to maintain food security in the face of compounding threats. An effective governance framework requires coordination across institutions, real-time monitoring, risk assessment protocols, and contingency planning that bridges the environmental and cyber domains.

Recognizing this interconnectedness also shifts the focus from reactive crisis management to proactive resilience building. By anticipating compound threats, integrating technological solutions with sustainable environmental practices, and strengthening institutional capacity, Algeria can reduce vulnerability to cascading disruptions. This approach ensures that food security is maintained even under conditions of heightened environmental stress and digital vulnerability, providing a foundation for sustainable and adaptive national strategies. This shift towards a comprehensive governance model ultimately necessitates a robust nexus approach that balances the extraction of water resources with the adoption of renewable energy, ensuring that technological reliance does not inadvertently compromise environmental sustainability (Mostefaoui et al., 2024, p. 21).

## 3. Environmental Risks Affecting Food Security in Algeria

### 3.1 Climate Change and Agricultural Vulnerability

Climate change has emerged as one of the most significant challenges facing food security systems around the world. For countries characterized by arid and semi-arid environments, such as Algeria, the consequences are particularly severe. Rising temperatures, changing precipitation patterns, increased frequency of extreme weather events, and prolonged drought periods directly affect agricultural productivity and threaten the sustainability of food systems. These environmental transformations are no longer future concerns but present realities that increasingly shape agricultural performance and national food security outcomes. Specifically, the country's structural reliance on rain-fed agriculture exacerbates these vulnerabilities, as intermittent rainfall and insufficient water resource management significantly impede yield stability (Benbekhti et al., 2024).

Algeria's agricultural sector is highly sensitive to climatic fluctuations because a substantial portion of agricultural production remains dependent on natural rainfall. Variations in rainfall distribution can significantly alter planting schedules, crop development, and harvest yields. Years characterized by reduced precipitation often result in lower cereal production, forcing the country to increase imports in order to satisfy domestic demand. This dependency creates additional economic pressures and increases exposure to external market volatility. To counter these systemic weaknesses, the adoption of resilience-enhancing measures such as the implementation of climate-resilient seed varieties and expanded irrigation infrastructure has become essential for stabilizing domestic productivity (Elkhalfi et al., 2025).

The effects of climate change extend beyond crop production. Livestock systems are also affected by deteriorating pasture conditions, reduced water availability, and increasing heat stress. These factors contribute to declining productivity and rising production costs. At the same time, higher temperatures accelerate water evaporation, reduce soil moisture retention, and increase the frequency of wildfires in vulnerable ecosystems. Such developments further undermine agricultural sustainability and rural livelihoods.

Another critical concern relates to the growing unpredictability of climatic conditions. Traditional agricultural planning relies heavily on seasonal patterns and historical climate data. However, climate change disrupts these patterns, making agricultural forecasting increasingly difficult. Farmers often face uncertainty regarding planting periods, irrigation requirements, and expected yields. This uncertainty complicates decision-making processes and increases financial risks for agricultural producers. Furthermore, projected declines in total annual precipitation of 15–30%, coupled with rising temperatures, threaten to shift climatic zones and accelerate desertification, further destabilizing the temperate northern regions that serve as the country's agricultural backbone (al., 2021, p. 982; Boudebbouz et al., 2023, p. 124).

Addressing climate-related challenges requires long-term adaptation strategies that integrate scientific research, technological innovation, and sustainable resource management. Investments in drought-resistant crop varieties, climate-smart agricultural practices, and advanced monitoring systems can help reduce vulnerability. However, adaptation efforts must be accompanied by strong governance mechanisms capable of coordinating actions across environmental, agricultural, and economic sectors. Building resilience to climate change is therefore not solely a technical challenge but also an institutional and strategic imperative for Algeria's future food security.

**3.2 Water Stress as a Structural Challenge**

Among all environmental constraints affecting Algeria's food system, water scarcity represents the most critical and persistent challenge. Water is an indispensable resource for agricultural production, and its availability directly influences crop yields, livestock development, and overall food system stability. Algeria's geographical location and climatic conditions place the country among regions experiencing chronic water stress, a situation expected to intensify under future climate scenarios. The depletion of non-renewable groundwater reserves, compounded by the increasing recurrence of extreme drought events, necessitates a transition toward non-conventional water sourcing and optimized irrigation efficiency to sustain rural output (Bessaoud et al., 2019, p. 47; Hadjout et al., 2025, p. 6705).

The distribution of water resources across Algeria is highly uneven. Northern regions, which host the majority of agricultural activity and population concentration, experience significant pressure on available water supplies. Meanwhile, substantial groundwater reserves exist in southern desert areas, yet exploiting these resources presents considerable technical, financial, and environmental challenges. This geographical imbalance creates structural constraints that complicate agricultural development and long-term food security planning.

Rapid population growth and urbanization further intensify competition for water resources. Agriculture must increasingly compete with domestic consumption, industrial development, and energy production for limited supplies. As demand rises across multiple sectors, the challenge of allocating water efficiently becomes more complex. Without effective management strategies, resource shortages could undermine both agricultural productivity and broader economic stability. Consequently, the adoption of integrated water resource management frameworks is imperative to reconcile these competing sectoral demands and ensure the equitable distribution of hydrological assets (Borsetta, 2025; Moussaoui, 2025).

To address these challenges, Algeria has invested heavily in non-conventional water resources, particularly seawater desalination. Desalination plants have become an essential component of the national water strategy, providing an alternative source of freshwater for urban and industrial consumption. By reducing pressure on traditional water resources, desalination indirectly supports agricultural sustainability. However, these facilities require substantial energy inputs and depend on sophisticated technological systems, creating new operational and security challenges.

Water stress also has important social and economic implications. Reduced agricultural productivity can affect rural employment, increase food prices, and contribute to migration from agricultural regions. Such consequences demonstrate that water scarcity is not merely an environmental issue but a multidimensional challenge affecting social cohesion, economic development, and national resilience. Effective responses therefore require integrated governance approaches that combine technological innovation, environmental sustainability, and strategic planning to ensure long-term water security.

### 3.3 Desertification and Land Degradation

Desertification represents another major environmental threat affecting Algeria's agricultural potential and food security. The process involves the gradual degradation of land in arid and semi-arid regions due to a combination of climatic factors and human activities. As productive land loses its fertility and ecological functionality, agricultural output declines, increasing pressure on food systems already facing multiple challenges. Moreover, the persistent expansion of irrigated areas—which grew from 350,000 hectares in 2000 to over 1.3 million hectares by 2020—often occurs in regions where irrigation efficiency remains below national averages, exacerbating soil salinization and resource depletion (Mezouane et al., 2025).

Algeria's vast territory includes extensive areas vulnerable to desertification. Rising temperatures, reduced rainfall, overgrazing, deforestation, and unsustainable land-use practices contribute to the expansion of degraded landscapes. The gradual loss of vegetation cover accelerates soil erosion, reduces water infiltration, and weakens the capacity of ecosystems to support agricultural activities. These processes create long-term structural challenges that cannot be resolved through short-term interventions alone.

Land degradation directly affects agricultural productivity by reducing soil fertility and limiting the availability of nutrients necessary for crop growth. Farmers operating in degraded areas often experience declining yields despite increasing production efforts. In some regions, agricultural activities become economically unsustainable, forcing communities to abandon traditional livelihoods. Such developments contribute to rural vulnerability and increase dependence on external food supplies.

The interaction between desertification and climate change further amplifies risks. Drier conditions accelerate land degradation, while degraded soils become less capable of retaining moisture and supporting vegetation. This creates a self-reinforcing cycle in which environmental deterioration continuously undermines agricultural resilience. Breaking this cycle requires comprehensive land management policies focused on conservation, restoration, and sustainable agricultural practices. Specifically, current mitigation strategies emphasize the rehabilitation of the Green Dam to curb the rapid advancement of arid zones, while simultaneously addressing the severe soil loss caused by torrential rainfall and wind activity (Change, 2022, p. 309).

Efforts to combat desertification must involve multiple stakeholders, including government institutions, local communities, research organizations, and private sector actors. Reforestation programs, sustainable grazing management, soil conservation techniques, and ecosystem restoration initiatives can contribute significantly to preserving productive land. These measures not only support agricultural development but also strengthen environmental resilience more broadly. Given the strategic importance of agricultural land for national food security, addressing desertification should remain a central priority within Algeria's environmental and agricultural policy agenda.

### 3.4 Environmental Resilience as a Strategic Imperative

The increasing intensity and frequency of environmental challenges have elevated resilience from a theoretical concept to a strategic necessity. Environmental resilience refers to the capacity of ecosystems, institutions, and communities to absorb shocks, adapt to changing conditions, and maintain essential functions despite disruptions. Within the context of food security, resilience determines whether agricultural systems can continue producing food under conditions of environmental uncertainty. This imperative requires shifting toward climate-smart agricultural frameworks that prioritize soil health and resource efficiency, thereby mitigating the vulnerability of the national food supply to extreme climatic shifts (Hammad, 2025; Raihan, 2023, p. 51).

For Algeria, strengthening environmental resilience requires moving beyond reactive responses to environmental crises. Traditional approaches often focus on emergency interventions following droughts, water shortages, or production failures. While such measures remain important, they do not address the underlying vulnerabilities that generate recurring crises. A resilience-oriented strategy seeks instead to reduce exposure to risks and enhance adaptive capacity before disruptions occur.

Technological innovation plays an important role in this process. Precision agriculture, climate monitoring systems, remote sensing technologies, and advanced irrigation techniques can improve resource efficiency and support informed decision-making. These tools enable farmers and policymakers to anticipate environmental changes and respond more effectively to emerging threats. However, technology alone cannot guarantee resilience. Institutional capacity, governance quality, and stakeholder coordination are equally important components. Furthermore, integrating resilience-building measures into policy frameworks ensures that social protection programs provide a necessary buffer for farmers facing these multifaceted environmental shocks (Banso et al., 2023, p. 252).

Environmental resilience also requires integrating sustainability principles into agricultural development strategies. Resource conservation, ecosystem protection, and sustainable land management practices contribute to maintaining the long-term productivity of agricultural systems. Policies that prioritize short-term production gains at the expense of environmental sustainability may ultimately weaken resilience and increase vulnerability to future shocks.

The concept of resilience therefore provides a valuable framework for understanding how Algeria can navigate environmental uncertainty while maintaining food security. By investing in adaptive capacity, strengthening governance mechanisms, and promoting sustainable development, the country can reduce vulnerability to environmental risks and create a more robust foundation for future agricultural growth. Such efforts become even more important when considering the interaction between environmental challenges and emerging technological risks, which together shape the evolving landscape of food security governance. Consequently, achieving this stability necessitates a critical balancing act for policymakers, who must simultaneously pursue higher production yields and foster systemic robustness to mitigate the impact of climate-induced shocks (Coomes et al., 2018, p. 26).

## 4. Cyber Risks Affecting Food Security in Algeria

### 4.1 Digital Transformation in Agriculture

The agricultural sector in Algeria is undergoing a gradual but significant digital transformation, often referred to as Agriculture 4.0. This transformation involves the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), remote sensing, automated irrigation systems, and precision farming tools. The objective is to improve productivity, optimize resource utilization, and enable data-driven decision-making in agricultural management. These technologies offer immense potential to increase crop yields, reduce wastage, and improve water and energy efficiency, addressing some of the structural constraints that have historically limited Algerian agriculture. However, this digital integration simultaneously introduces systemic vulnerabilities, as reliance on interconnected digital infrastructures exposes critical food production and distribution networks to potential cyber threats (Mechta & Belkacemi, 2025).

However, digital transformation also introduces new vulnerabilities. Modern agricultural systems rely heavily on interconnected digital platforms and networks that collect, process, and store critical information, such as soil moisture levels, crop health data, climate forecasts, and supply chain logistics. Any disruption in these systems—whether through technical failure, cyberattack, or operational errors—can severely affect agricultural output. The more Algeria depends on digital tools to monitor, manage, and automate farming operations, the greater the potential impact of cyber incidents on national food security.

Additionally, Algeria's digital infrastructure in agriculture is still developing and exhibits significant disparities. Urban and industrial regions often benefit from better technological access and skilled personnel, while rural farming communities may have limited connectivity and technical support. This uneven distribution of digital capacity can create gaps in security preparedness, leaving some segments of the agricultural sector more vulnerable to cyber threats than others. Without a coordinated strategy, isolated technological advancements may inadvertently increase systemic risks rather than mitigate them.

### 4.2 Cybersecurity Threats in Agricultural Infrastructure

Cybersecurity threats in agriculture are evolving in both sophistication and scale. Globally, the agriculture sector has witnessed attacks targeting supply chains, production machinery, and data management systems. In Algeria, smart irrigation systems, automated greenhouses, and digital logistics platforms represent high-value targets for potential cyberattacks. These threats include ransomware, malware infections, unauthorized access, and data manipulation, all of which can disrupt operations, compromise sensitive information, and create economic losses. Furthermore, the interconnected nature of these systems implies that a breach in one component can cascade throughout the supply chain, endangering food accessibility and national availability (Kulkarni et al., 2024, p. 18).

One particular concern is the vulnerability of industrial control systems (ICS) that manage irrigation networks, water pumps, and desalination operations. Cyber intrusions in these systems can cause operational disruptions that directly affect crop irrigation schedules and water availability. In an environment already challenged by water scarcity and climate variability, such disruptions could have cascading effects on food production, distribution, and access, highlighting the critical link between cyber resilience and environmental security.

Another dimension of cyber risk involves the manipulation of agricultural data. Incorrect or tampered data on crop yields, soil conditions, or market inventories can mislead policymakers and farmers, leading to inefficient allocation of resources and delayed responses to emerging crises. Furthermore, cyberattacks on supply chain management platforms can impede logistics, causing delays in the delivery of essential inputs such as seeds, fertilizers, and machinery, which are critical to maintaining production continuity.

The interdependence of digital systems and agricultural operations underscores the need for comprehensive cybersecurity strategies. Beyond protecting individual systems, these strategies must ensure the resilience of entire networks, including monitoring, early warning mechanisms, incident response protocols, and institutional coordination. Cybersecurity in agriculture is no longer merely an IT concern; it has become a core element of national food security planning. Addressing these vulnerabilities requires a multifaceted approach, including the implementation of robust encryption protocols, continuous IoT vulnerability assessments, and specialized training to enhance the cyber-literacy of rural stakeholders (Adewusi et al., 2022).

### 4.3 Supply Chain Vulnerabilities and Geopolitical Implications

Algeria's dependence on imports for key commodities, particularly cereals, adds a geopolitical layer to its food security vulnerabilities. Digital systems managing imports, logistics, and distribution networks are critical for ensuring that these commodities reach local markets efficiently. Any disruption in these systems—whether through cyberattacks, technical failures, or supply chain bottlenecks—can amplify existing vulnerabilities caused by domestic production deficits and environmental stress.

Geopolitical tensions further exacerbate these risks. Algeria must navigate complex trade relationships and fluctuating international market conditions. Disruptions in supplier countries, sanctions, or logistical challenges can have immediate and severe effects on food availability. When combined with domestic cyber vulnerabilities, these external shocks create a compound risk environment in which multiple threats interact simultaneously, magnifying potential consequences for food security. Moreover, the integration of centralized control systems in storage and distribution facilities often lacks the necessary security protocols to prevent sophisticated cyber-espionage and unauthorized interference (Yisa et al., 2023).

The digitalization of agricultural trade, including online tender platforms, supply monitoring systems, and automated customs procedures, introduces both opportunities and risks. While these technologies improve efficiency and transparency, they also create attack surfaces that can be exploited by malicious actors. A cyberattack on a critical port or customs platform could delay shipments, disrupt distribution networks, and trigger cascading shortages, illustrating the interconnected nature of technological, environmental, and geopolitical vulnerabilities.

### 4.4 Cyber Resilience as a Strategic Necessity

Given the growing complexity of digital threats, building cyber resilience in Algeria's agricultural sector is no longer optional—it is a strategic necessity. Cyber resilience extends beyond the traditional concept of cybersecurity by focusing not only on prevention but also on the capacity to absorb shocks, maintain essential functions during disruptions, and recover quickly after incidents occur. In the context of food security, this involves ensuring that production systems, water management infrastructure, logistics networks, and supply chains can continue operating effectively despite cyber incidents.

Developing cyber resilience requires a multi-layered approach. First, technological safeguards such as firewalls, encryption, intrusion detection systems, and secure access controls are essential to protect individual systems. Second, institutional frameworks must enable coordinated responses, rapid incident reporting, and continuous monitoring of vulnerabilities. Third, human capacity must be strengthened through specialized training programs, awareness campaigns, and skills development for agricultural managers, technicians, and policymakers. Finally, fostering collaboration between technology providers, government agencies, and the agricultural workforce is vital to establishing and maintaining standardized best practices that strengthen the overall resilience of the sector against emerging threats (Ongadi, 2024, p. 345).

The benefits of cyber resilience extend beyond protecting digital assets. By ensuring the continuity of critical agricultural operations, cyber resilience directly supports food security and national stability. It enables Algeria to maintain production levels, secure supply chains, and reduce exposure to external shocks, particularly when environmental risks, such as droughts or water shortages, interact with technological vulnerabilities. Cyber resilience is therefore an indispensable component of a holistic strategy to safeguard Algeria's food system in an increasingly complex and uncertain world.

## 5. Toward an Integrated Governance Model for Food Security in Algeria

### 5.1 Rethinking Food Security Governance in an Era of Complex Risks

The growing interaction between environmental pressures and cyber vulnerabilities requires a fundamental rethinking of how food security is governed in Algeria. Traditional governance models were primarily designed to address isolated challenges such as agricultural production deficits, market fluctuations, or climatic shocks. While these approaches remain relevant, they are increasingly insufficient in a context where multiple risks interact simultaneously and generate cascading effects across interconnected systems. Modern food security governance must therefore evolve from a sector-based approach toward a systemic and integrated framework capable of addressing complex and overlapping threats. This transition necessitates the development of comprehensive financing programs and strategic policy frameworks that explicitly account for the nexus between environmental sustainability and digital infrastructure security (Draou, 2022; Obasi et al., 2024, p. 1154).

The concept of integrated governance is based on the recognition that food systems are not isolated entities. They are deeply connected to water management, energy production, transportation networks, digital infrastructure, environmental sustainability, and international trade. A disruption in one of these sectors can rapidly affect the entire food system. For example, a severe drought may reduce agricultural production, while a cyberattack targeting irrigation systems could further aggravate water shortages and amplify the impact on food availability. Similarly, disruptions in logistics platforms may compromise the distribution of imported food products, even when sufficient supplies are available.

Within this context, governance should focus not only on managing individual risks but also on understanding and addressing the interactions between them. This requires stronger institutional coordination, improved information sharing, and the development of comprehensive risk assessment mechanisms capable of identifying vulnerabilities before they evolve into crises. Food security policies must incorporate environmental monitoring systems, cybersecurity strategies, emergency preparedness plans, and long-term sustainability objectives within a single strategic framework. Such an approach aligns with the necessity of addressing cross-sector interactions, which have become increasingly critical due to natural resource scarcity and fragmented governance structures (Azizi, 2020, p. 328).

A shift toward integrated governance also implies adopting a proactive rather than reactive approach. Instead of responding to crises after they occur, institutions should prioritize anticipation, prevention, and resilience-building measures. Such an approach enables governments to reduce vulnerability, improve adaptability, and maintain operational continuity under conditions of uncertainty. For Algeria, where environmental stress, technological transformation, and geopolitical uncertainty increasingly intersect, the development of an integrated governance model represents a strategic necessity for safeguarding national food security.

**5.2 Strengthening Environmental Resilience**

Environmental resilience constitutes one of the most important pillars of food security governance. Given the increasing severity of climate change impacts, Algeria must prioritize strategies that enhance the ability of agricultural systems to withstand environmental shocks while maintaining sustainable levels of production. Building environmental resilience requires a combination of technological innovation, institutional reform, sustainable resource management, and long-term strategic planning. Specifically, this involves implementing land tenure reforms to incentivize local stewardship of natural resources while simultaneously deploying advanced drought-resistant irrigation technologies (Stavi et al., 2021, p. 1358).

One of the primary priorities should be the modernization of water management systems. Efficient irrigation technologies, water-saving agricultural practices, and improved monitoring of water resources can significantly reduce vulnerability to drought and water scarcity. The adoption of precision agriculture technologies can further enhance resource efficiency by enabling farmers to apply water, fertilizers, and other inputs more accurately based on real-time data and environmental conditions.

Climate adaptation measures are equally important. Developing drought-resistant crop varieties, diversifying agricultural production systems, and promoting climate-smart farming practices can improve the capacity of farmers to adapt to changing environmental conditions. Such measures reduce dependence on favorable climatic conditions and contribute to the long-term sustainability of agricultural production.

Environmental resilience also depends on preserving ecosystems and combating land degradation. Sustainable land management practices, reforestation programs, and soil conservation initiatives help maintain agricultural productivity while reducing vulnerability to desertification. These measures not only support food production but also contribute to broader environmental objectives, including biodiversity conservation and carbon sequestration.

Institutional coordination plays a crucial role in implementing environmental resilience strategies. Effective adaptation requires collaboration among ministries responsible for agriculture, water resources, environment, research, and regional development. By integrating environmental considerations into broader food security policies, Algeria can strengthen its capacity to respond to current challenges while preparing for future uncertainties. Environmental resilience should therefore be viewed not as a separate policy objective but as an essential component of national food security governance.

**5.3 Building Cyber Resilience Across the Food System**

As agriculture becomes increasingly digitized, cyber resilience emerges as a critical component of food security governance. Digital technologies now support essential agricultural functions, including irrigation management, crop monitoring, logistics coordination, market information systems, and resource planning. While these technologies improve efficiency and productivity, they also create new vulnerabilities that can threaten the continuity of food production and distribution.

Building cyber resilience requires a comprehensive strategy that extends beyond technical cybersecurity measures. Protective technologies such as encryption, firewalls, access controls, and intrusion detection systems are important, but they represent only one dimension of resilience. Effective governance must also address organizational preparedness, workforce development, regulatory frameworks, and institutional coordination. Establishing protocols for real-time information control allows authorities to maintain oversight of sensitive agricultural data while mitigating the impact of potential digital disruptions (Yang & Cong-hua, 2024, p. 21).

One priority area involves securing critical infrastructure. Water treatment facilities, desalination plants, irrigation networks, storage facilities, and transportation systems increasingly rely on digital control systems that may become targets of cyberattacks. Protecting these assets requires regular risk assessments, vulnerability testing, and the implementation of robust security protocols. Operational continuity plans should also be established to ensure that essential services remain functional during cyber incidents.

Human capacity development is equally important. Many cyber incidents result from human error, inadequate awareness, or insufficient technical expertise. Training programs for agricultural managers, engineers, technicians, and policymakers can significantly enhance resilience by improving understanding of cyber risks and promoting best practices in digital security management. Universities and research institutions can also contribute by developing specialized expertise in agricultural cybersecurity.

At the governance level, stronger cooperation between cybersecurity authorities and agricultural institutions is essential. Information sharing mechanisms, joint risk assessments, and coordinated response strategies can improve preparedness and accelerate recovery efforts when incidents occur. By embedding cybersecurity considerations into agricultural modernization programs, Algeria can ensure that technological innovation contributes to resilience rather than creating new sources of vulnerability. Furthermore, integrating emerging technologies like artificial intelligence and blockchain can strengthen data sovereignty and provide the necessary safeguards to maintain system integrity against sophisticated digital threats (Mıjwıl et al., 2023, p. 2; Shalini et al., 2026).

**5.4 Policy Integration and Institutional Coordination**

One of the most significant challenges facing food security governance in Algeria is the fragmentation of policies and institutional responsibilities. Environmental management, agricultural development, water governance, digital transformation, and cybersecurity are often addressed through separate policy frameworks with limited coordination among relevant actors.

This fragmentation reduces efficiency, creates governance gaps, and limits the ability of institutions to respond effectively to complex risks.

An integrated governance model requires the establishment of mechanisms that facilitate cooperation across sectors and institutions. National strategies should explicitly recognize the interdependence of environmental and cyber risks and incorporate both dimensions into food security planning. This can be achieved through interministerial committees, joint monitoring systems, shared databases, and coordinated emergency response protocols.

Data integration represents another important priority. Effective decision-making depends on access to reliable information regarding environmental conditions, agricultural production, water resources, and cybersecurity threats. Developing integrated information platforms can improve situational awareness and support evidence-based policymaking. Such systems can also enhance early warning capabilities by identifying emerging risks before they escalate into major crises.

Research and innovation should be positioned at the center of policy integration efforts. Universities, research centers, and technology developers can provide valuable insights into emerging threats, adaptation strategies, and resilience-building measures. Strengthening collaboration between academic institutions and government agencies can improve policy effectiveness and support continuous learning in response to evolving challenges. Moreover, ensuring policy alignment and harmonization across national frameworks is essential to prevent the duplication of efforts and bridge the gap between high-level strategic formulation and operational implementation (Kebede et al., 2024, p. 307).

Ultimately, institutional coordination is not merely an administrative objective; it is a prerequisite for resilience. Complex risks cannot be managed effectively through isolated interventions. By fostering collaboration, integrating policies, and promoting a shared understanding of systemic vulnerabilities, Algeria can strengthen the governance foundations necessary to ensure long-term food security in an increasingly uncertain global environment.

## 6. Findings and Discussion

### 6.1 Key Findings

The analysis conducted throughout this study reveals that food security in Algeria is shaped by a combination of environmental, technological, and geopolitical factors that interact in increasingly complex ways. Environmental pressures, particularly water scarcity, climate variability, and land degradation, continue to represent structural constraints on agricultural production. At the same time, the digital transformation of agriculture introduces new vulnerabilities related to cybersecurity and technological dependence.

The study demonstrates that these risks do not operate independently. Environmental challenges often increase reliance on digital technologies, while cyber vulnerabilities can magnify the consequences of environmental shocks. This interaction creates compound risks that cannot be addressed effectively through traditional sector-based approaches. Consequently, resilience depends on the ability of institutions to manage these risks collectively rather than individually. Furthermore, the evidence suggests that promoting integrated management strategies—as seen in broader international contexts—is vital to balancing sustainability objectives with production security (Cano-Lamadrid et al., 2025, p. 3).

The findings also indicate that Algeria has made notable progress in areas such as agricultural modernization, water infrastructure development, and digital transformation. However, these advances remain constrained by institutional fragmentation, limited policy integration, and insufficient attention to the intersection between environmental and cyber resilience. Addressing these gaps will be essential for strengthening the country's long-term food security capacity.

**6.2 Discussion of Findings**

The analysis highlights a critical insight: Algeria’s food security is not determined solely by agricultural output or import dependency. Instead, it is shaped by a dynamic interplay between environmental pressures, technological vulnerabilities, and geopolitical factors. Water scarcity, desertification, and climate variability act as structural constraints, limiting agricultural productivity and increasing reliance on imported cereals. Simultaneously, the digitization of agricultural operations, while offering efficiency gains, introduces cyber vulnerabilities that may disrupt irrigation, production, and supply chain operations. These dual pressures illustrate that risks are interconnected, creating a complex environment in which failures in one domain can amplify vulnerabilities across others. To mitigate these systemic risks, transitioning toward a water-energy-food nexus approach is imperative for reducing fossil fuel dependence while diversifying essential resource supplies (Bouchentouf & BENABDELI, 2021, p. 422).

Furthermore, the study reveals that existing policies and institutional frameworks are fragmented, with environmental governance, cybersecurity, and agricultural management often functioning in isolation. This lack of coordination reduces the capacity to respond effectively to compound risks. For example, while water resource management programs may improve infrastructure, they often do not account for the cybersecurity of control systems. Similarly, investments in digital agricultural technologies may increase operational efficiency but simultaneously introduce new points of failure that are not systematically addressed in national risk assessments. This misalignment underscores the necessity of a more integrated approach to governance. This institutional synchronization requires the adoption of nexus-based planning, which prioritizes the interdependencies between water, energy, and food systems to facilitate proactive, evidence-based policy design (Daher et al., 2022, p. 12; García, 2023, p. 106).

The findings also suggest that resilience depends on proactive, rather than reactive, strategies. Reactive responses, such as emergency water allocations or crisis-driven cybersecurity interventions, are insufficient to manage complex risks. Instead, Algeria must adopt forward-looking measures that anticipate environmental stress, secure digital infrastructure, and maintain continuity across the food system. Proactive risk governance, supported by integrated policy frameworks and institutional coordination, enhances the capacity to absorb shocks, adapt to changing conditions, and recover quickly from disruptions. Moreover, embedding diverse stakeholder perspectives into the nexus governance framework ensures that sustainability transitions align with ecological limits and cultural values, thereby fostering more robust human–nature relationships (Garau et al., 2025, p. 17).

Finally, the discussion emphasizes that technological adoption alone cannot guarantee food security. While smart irrigation, precision agriculture, and IoT-enabled monitoring provide valuable tools, their effectiveness relies on parallel investments in governance, capacity building, and institutional oversight. Without these measures, technological advances may inadvertently exacerbate vulnerabilities, creating dependencies on external systems or exposing critical infrastructure to cyber threats. Therefore, Algeria's path toward resilient food security requires harmonized action across environmental management, technological safeguards, and institutional integration. Leveraging reflexive governance, which engages diverse actors such as policymakers, entrepreneurs, and civil society, can facilitate the multi-sectoral collaboration necessary to reshape these structures as conditions evolve (Liu et al., 2018, p. 476).

## 7. Recommendations

Based on the findings and discussion, the following recommendations are proposed to strengthen Algeria's food security in the context of compound environmental and cyber risks:

Integrate Environmental and Cyber Policies: Develop a comprehensive governance framework that aligns water resource management, climate adaptation, agricultural planning, and cybersecurity strategies under a single national food security strategy.

Enhance Digital Infrastructure Security: Implement robust cybersecurity protocols for agricultural and water management systems, including intrusion detection, access controls, and contingency planning to ensure operational continuity during cyber incidents.

Strengthen Environmental Resilience: Invest in climate-smart agriculture, drought-resistant crop varieties, sustainable land management, and modern irrigation technologies to mitigate the impact of environmental stressors on agricultural productivity.

Build Institutional Capacity: Promote coordination between ministries, agencies, and research institutions to ensure information sharing, joint risk assessments, and effective crisis management across the food system.

Develop Human Capital: Train agricultural managers, technical staff, and policymakers in both environmental management and digital security, fostering expertise that bridges technological, ecological, and operational domains.

Monitor and Diversify Supply Chains: Reduce vulnerability to import disruptions through supplier diversification, strategic reserves, and monitoring of global market dynamics, while integrating digital monitoring tools to enhance logistics resilience.

Adopt a Proactive Risk Management Approach: Shift from reactive interventions toward anticipatory strategies that identify and mitigate emerging risks before they escalate, ensuring long-term sustainability and system adaptability.

## Conclusion:

Algeria's food security is increasingly shaped by the interaction of environmental and cyber risks, creating a landscape of complex, interdependent vulnerabilities. Climate variability, water scarcity, and land degradation constrain domestic agricultural production, while digital transformation introduces new risks in irrigation, production management, and supply chains. Existing policy fragmentation and limited institutional coordination exacerbate these vulnerabilities, highlighting the need for integrated governance mechanisms.

Strengthening food security requires a dual focus on environmental resilience and cyber preparedness. Technological innovation, sustainable resource management, and climate-smart agriculture must be paired with robust cybersecurity, institutional coordination, and proactive risk governance. By adopting a comprehensive approach that addresses the compound nature of contemporary risks, Algeria can enhance the resilience of its food systems, safeguard national sovereignty over critical resources, and ensure long-term access to safe and nutritious food for its population.

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