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Impact of Climate Change on Surgical Health Systems: Vulnerabilities and Resilience Strategies

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Abstract

Climate change is increasingly recognized as a major threat to health systems, yet its implications for surgical care remain underexplored. Surgical health systems are particularly vulnerable because they rely on uninterrupted infrastructure, stable supply chains, skilled personnel, and resource-intensive technologies. Climate-related hazards, including extreme heat, floods, storms, wildfires, and sea-level rise, can disrupt surgical service delivery by damaging healthcare facilities, interrupting electricity and water supplies, delaying the availability of essential medicines and equipment, and limiting workforce capacity. These disruptions compromise timely access to surgical care, increase perioperative risks, and exacerbate existing inequities, especially in low- and middle-income countries where surgical systems often operate under constrained resources. This review explains current evidence on the pathways through which climate change affects surgical health systems and critically examines strategies for enhancing system resilience. Key resilience approaches include climate-resilient healthcare infrastructure, sustainable procurement and supply chain management, workforce preparedness, disaster-informed surgical planning, supportive governance, and the integration of digital health technologies to strengthen service continuity. The review also highlights emerging innovations and identifies research priorities needed to improve adaptive capacity and inform evidence-based policy. Strengthening the resilience of surgical health systems is essential not only for maintaining safe and equitable surgical care during climate-related disruptions but also for advancing broader health system sustainability. The findings provide a comprehensive framework to guide policymakers, healthcare leaders, and researchers in developing climate-resilient surgical services capable of meeting current and future challenges.

Keywords: *Climate change, Surgical health systems, Health system resilience, Surgical infrastructure, Disaster preparedness and Sustainable healthcare.*

Introduction

Climate change has emerged as one of the most significant threats to global health, affecting the capacity of health systems to deliver safe, accessible, and high-quality care. Rising temperatures, extreme weather events, floods, droughts, wildfires, and sea-level rise are increasing in frequency and severity, disrupting healthcare infrastructure and essential medical services across diverse settings [1]. These escalating environmental hazards are redefining healthcare preparedness and service delivery, requiring health systems to adapt to increasingly complex and unpredictable conditions [2]. Although considerable attention has been devoted to the effects of climate change on public health, its implications for surgical health systems remain comparatively underexplored despite surgery being an indispensable component of modern healthcare.

Surgical health systems depend on reliable infrastructure, uninterrupted electricity and water supplies, efficient supply chains, functional operating theatres, and a skilled multidisciplinary workforce to provide timely and safe care [2]. Climate-related disasters can damage hospitals, interrupt transportation networks, limit the availability of essential medicines and surgical equipment, and reduce workforce capacity during emergencies (Romanello *et al.,* 2024). Such disruptions frequently delay elective and emergency procedures, compromise perioperative safety, and exacerbate existing disparities in access to surgical care, particularly in low- and middle-income countries where health systems often operate with constrained resources [3]. These growing challenges underscore the need to strengthen the resilience of surgical services before, during, and after climate-related events.

Beyond disrupting healthcare delivery, climate change has also intensified the need to reduce the environmental impact of surgical practice. Surgical care is among the most resource-intensive components of healthcare because of its dependence on energy-intensive facilities, anaesthetic gases, sterilization processes, disposable equipment, and extensive supply chains [4]. Consequently, improving sustainability has become an essential strategy for enhancing both environmental stewardship and health system resilience. Recent evidence highlights opportunities to reduce waste, optimise resource utilisation, adopt lower-carbon technologies, and integrate environmentally responsible practices without compromising patient safety or clinical outcomes [5]. Embedding sustainability within surgical systems, therefore, supports both climate mitigation and long-term service continuity.

Resilient surgical health systems are designed to anticipate, withstand, adapt to, and recover from climate-related shocks while maintaining essential surgical services and protecting patient outcomes. Building such resilience requires coordinated investments in climate-resilient infrastructure, sustainable procurement, emergency preparedness, workforce training, governance, and digital innovation [6]. A resilient health system is not defined solely by its capacity to respond to emergencies but also by its ability to learn, adapt, and continuously improve following disruption [7]. Integrating resilience principles into surgical planning, therefore, provides an important framework for strengthening healthcare systems against the increasing health risks associated with climate change and ensuring the continuity of essential surgical care.

This review provides a comprehensive assessment of the impact of climate change on surgical health systems by examining the major vulnerabilities that threaten the delivery of safe, timely, and equitable surgical care. It explains current knowledge on how climate-related hazards influence healthcare infrastructure, essential utilities, supply chains, workforce capacity, service delivery, and surgical outcomes across different healthcare settings. The review further explores the interconnected challenges of maintaining essential surgical services while promoting environmental sustainability, emphasizing the importance of integrating resilience into surgical planning and health system development. Particular attention is given to practical resilience strategies, including climate-resilient infrastructure, sustainable resource management, emergency preparedness, workforce strengthening, digital health innovations, and effective governance that support continuity of care during environmental disruptions. Emerging technologies and future opportunities for building adaptive and sustainable surgical systems are also discussed to identify priority areas for research, policy, and clinical practice. By integrating evidence from climate science, global surgery, disaster preparedness, and health systems research, this review aims to provide a coherent framework for understanding the complex relationship between climate change and surgical care.

Ultimately, it seeks to inform researchers, healthcare professionals, hospital administrators, and policymakers on evidence-based approaches that strengthen the resilience, sustainability, and long-term performance of surgical health systems, thereby ensuring that essential surgical services remain accessible, safe, and responsive in the face of an evolving climate.

Climate Change and Surgical Health Systems

Climate change is reshaping the conditions under which surgical health systems operate, exposing them to a broad range of environmental, operational, and organisational challenges. Climate-related hazards not only disrupt the delivery of surgical services but also threaten the critical components that support safe, timely, and effective care [8]. Understanding these hazards and the vulnerabilities of surgical health systems provides the foundation for developing targeted adaptation and resilience strategies.

Climate Hazards Relevant to Surgical Care

Climate change is increasing the frequency and severity of hazards such as extreme heat, floods, storms, droughts, wildfires, and sea-level rise, all of which threaten the continuity of surgical care. These hazards damage healthcare infrastructure, disrupt transport, communication, electricity, and water supplies, and reduce the capacity of health systems to deliver safe perioperative services [9, 10]. Floods and storms can render operating theatres unusable, delay the transport of patients, personnel, medicines, blood products, and equipment, and interrupt essential utilities. Consequently, elective procedures are cancelled, emergency surgeries delayed, and perioperative morbidity increased.

Simultaneously, climate-related disasters often overwhelm hospitals with trauma patients while limiting institutional capacity, challenging emergency preparedness and resource allocation [11, 12]. Rising temperatures also impair surgical systems by increasing heat stress among healthcare workers, reducing concentration, productivity, and occupational safety, while escalating energy demands for hospital cooling, particularly in resource-constrained settings [13, 14]. Climate change further alters surgical demand through increases in climate-related injuries, displacement, and infectious diseases requiring surgical intervention, while drought-induced water scarcity compromises sterilisation, environmental cleaning, and hand hygiene [15]. Beyond healthcare facilities, climate-related disruptions to global supply chains reduce the availability of anaesthetic agents, implants, personal protective equipment, and other essential surgical supplies, exposing the vulnerability of modern surgical systems [16]. These interconnected challenges highlight the need for climate adaptation and preparedness to ensure resilient, safe, and equitable surgical care.

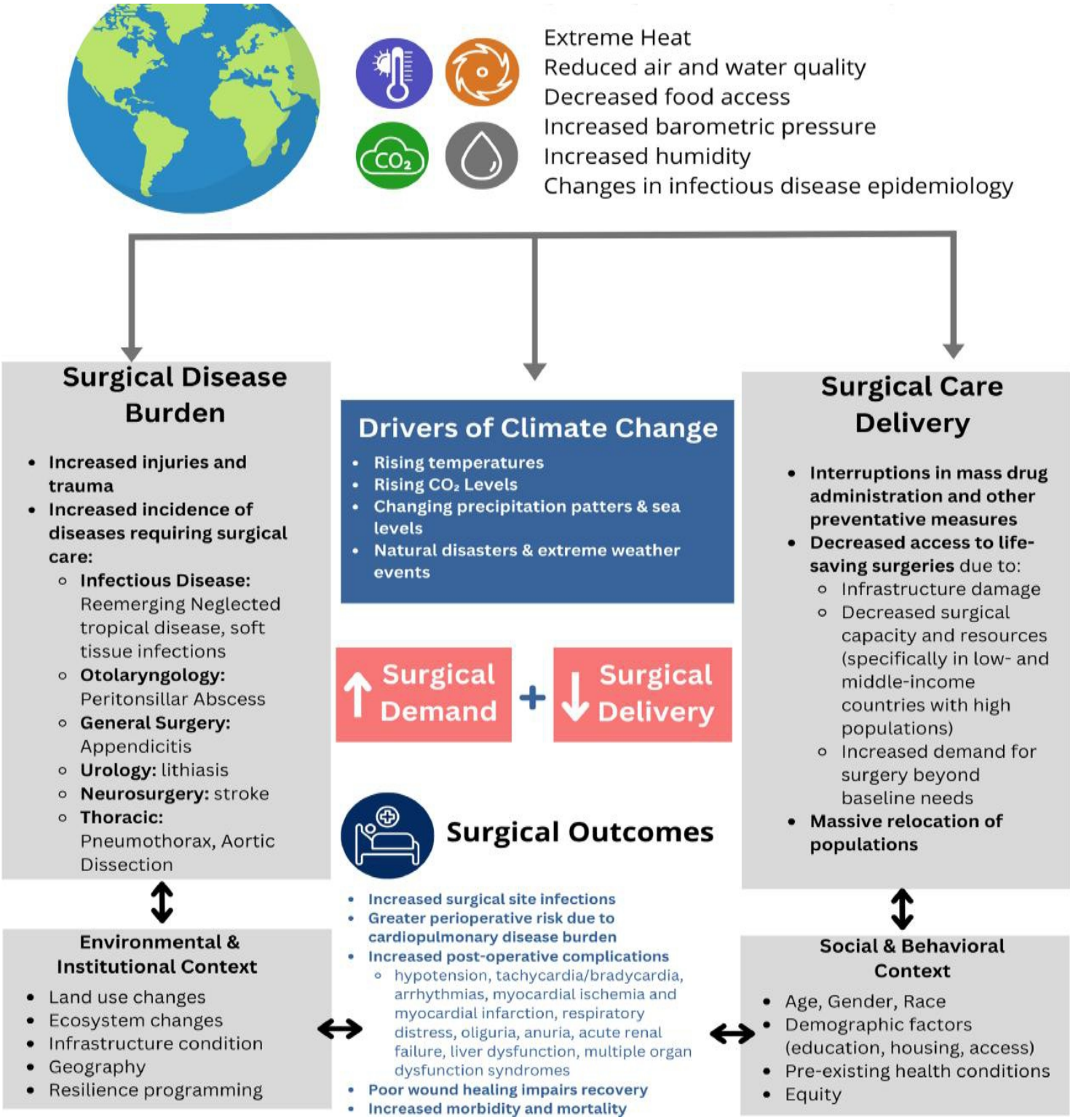

Figure 1: *Climate change pathways influencing surgical health systems and outcomes. Climate change generates multiple environmental hazards and exposure pathways that increase surgical disease burden, disrupt surgical care delivery, and worsen perioperative and postoperative outcomes. The impacts are mediated by environmental, institutional, social, and behavioral contexts, highlighting the complex interactions between climate hazards and surgical health systems.*

Source: *[1]*

Components of Surgical Health Systems at Risk

Climate change threatens every component of surgical health systems, exposing vulnerabilities that extend beyond individual facilities to the interconnected infrastructure, workforce, supply chains, governance, financing, and service delivery required for safe surgical care. Because these elements function interdependently, disruption to one component can compromise the entire surgical pathway [7]. Healthcare infrastructure is particularly vulnerable. Hospitals, operating theatres, intensive care units, sterilisation services, and diagnostic facilities rely on uninterrupted electricity, clean water, climate control, and waste management. Floods, storms, heatwaves, and wildfires can damage infrastructure and disrupt these essential utilities, underscoring the need for climate-resilient facility design, resilient utilities, and emergency preparedness to maintain surgical services during climate-related events [8, 9]. Supply chains are another major vulnerability. Surgical care depends on reliable access to medicines, anaesthetic agents, blood products, implants, sterile instruments, personal protective equipment, and diagnostic materials.

Climate-related disruptions to manufacturing, transport, or distribution can cause shortages that delay procedures and compromise patient safety. Strengthening supply chain resilience through diversified procurement and local production where feasible is therefore essential [1].

The surgical workforce is similarly at risk. Heat stress, disaster-related workload, displacement, and infrastructure disruption can reduce workforce availability, impair performance, and increase burnout. Building workforce resilience through emergency preparedness, occupational health measures, and adaptive workforce planning is critical for maintaining high-quality surgical care during climate-related emergencies [12, 13] Climate change also challenges service delivery and governance by increasing emergency surgical demand while disrupting routine care. Effective leadership, disaster preparedness, surveillance, sustainable financing, and policies that integrate climate adaptation are essential for maintaining equitable access to surgical services. Simultaneously, reducing the environmental footprint of perioperative care through resource-efficient practices, low-carbon technologies, waste reduction, and sustainable procurement can strengthen long-term health system resilience [14, 15].

Table 1: Components of surgical health systems at risk from climate change and their potential consequences

Surgical health system component	Climate-related threats	Potential consequences
Healthcare infrastructure	Floods, storms, heatwaves	Facility damage, reduced capacity
Utilities	Power outages, water scarcity	Disrupted operating theatres, sterilization failures
Supply chains	Transport disruption	Shortages of medicines and consumables
Workforce	Heat stress, disaster response	Reduced staffing, burnout
Information systems	Communication failures	Poor coordination and delayed care
Governance and financing	Resource diversion	Reduced preparedness and recovery

Vulnerabilities of Surgical Health Systems

Surgical health systems are particularly vulnerable to climate change because they depend on uninterrupted infrastructure, reliable utilities, resilient supply chains, a skilled workforce, and coordinated service delivery. Unlike many healthcare services, surgery requires continuous access to specialised facilities, advanced technologies, sterile environments, and multidisciplinary teams, making it highly sensitive to environmental disruptions [16]. As climate-related hazards become more frequent and severe, vulnerabilities within these interconnected components increasingly threaten the continuity, quality, and safety of surgical care. Addressing these weaknesses is fundamental to improving health system resilience and ensuring equitable access to essential surgical services under changing climatic conditions [17].

Infrastructure and Utility Disruptions

Healthcare infrastructure provides the physical and operational foundation for surgical care, but is increasingly threatened by climate-related hazards. Floods, storms, wildfires, and extreme heat can damage hospitals, operating theatres, intensive care units, sterilisation facilities, and diagnostic services, reducing their operational capacity during periods of greatest need [18]. Equally important are disruptions to essential utilities, including electricity, water, oxygen supply, ventilation systems, and digital communication networks, all of which are indispensable for safe perioperative care. Failures in these systems may interrupt surgical procedures, compromise infection prevention, and reduce critical care capacity [19].

Climate-resilient facility design, redundant utility systems, and comprehensive emergency preparedness plans have therefore become central strategies for maintaining continuity of surgical services during environmental emergencies [20].

Supply Chain and Resource Constraints

Modern surgical practice depends on complex supply networks that ensure the continuous availability of medicines, anaesthetic agents, blood products, implants, sterile instruments, consumables, and diagnostic equipment. Climate-related disasters frequently disrupt transportation, manufacturing, storage, and distribution systems, creating shortages that delay operations and compromise patient safety [21]. These vulnerabilities are amplified by the globalisation of medical supply chains, where localised climate events may produce widespread shortages across geographically distant healthcare systems [22]. At the same time, operating theatres remain among the most resource-intensive areas of healthcare, generating substantial material waste and carbon emissions [23]. Recent evidence supports circular economy principles, sustainable procurement, waste minimisation, and resource-efficient perioperative practices as practical approaches for improving both environmental sustainability and supply chain resilience [24].

Workforce and Service Delivery Challenges

The surgical workforce constitutes another critical point of vulnerability. Surgeons, anaesthetists, nurses, technicians, and support staff face increasing occupational risks associated with extreme heat, prolonged emergency response, psychological stress, and infrastructure disruption.

These conditions can impair physical performance, reduce cognitive function, increase fatigue, and contribute to workforce shortages during climate-related emergencies [25]. Simultaneously, healthcare facilities must accommodate surges in trauma and emergency surgical cases while maintaining routine elective services, placing considerable pressure on already constrained personnel and resources [26]. Building workforce resilience requires continuous professional training, adaptive workforce planning, multidisciplinary collaboration, and investment in climate-informed leadership and capacity building [27]. Optimising operating room organisation and perioperative workflows can further improve efficiency, resource utilisation, and service continuity during periods of operational stress [22].

Effects on Surgical Patients and Outcomes

The cumulative effects of infrastructure failures, resource shortages, and workforce constraints ultimately compromise patient outcomes. Delayed emergency interventions, postponed elective procedures, and interrupted perioperative care may increase disease progression, postoperative complications, prolonged hospitalisation, and mortality [23]. Reduced access to clean water, reliable electricity, and sterilisation services also elevates the risk of surgical site infections and other healthcare-associated infections, particularly in resource-limited settings [22]. Vulnerable populations, including rural communities, older adults, individuals with chronic diseases, and populations affected by disasters, often experience disproportionate barriers to accessing timely surgical care, further widening existing health inequities [22]. Strengthening climate resilience across infrastructure, supply systems, workforce capacity, and governance is therefore essential for protecting patient safety, preserving surgical quality, and ensuring the long-term sustainability of surgical health systems in an increasingly unstable climate [2].

Table 2: Major vulnerabilities of surgical health systems and their consequences under climate change

Vulnerability domain	Climate-related drivers	Effects on surgical health systems	Consequences for patients
Infrastructure and utilities	Floods, storms, heatwaves, drought	Damage to hospitals, power and water failures, operating theatre disruption	Surgical delays, cancelled procedures, infection risk
Supply chain and resources	Transport disruption, manufacturing interruptions	Shortages of medicines, blood, implants, PPE, equipment	Reduced surgical capacity, compromised patient safety
Workforce and service delivery	Heat stress, disasters, staff displacement	Burnout, absenteeism, reduced workforce availability, workflow disruption	Delayed care, reduced quality of care
Patient outcomes	Combined system failures	Reduced access to surgery, compromised perioperative care	Increased morbidity, mortality, prolonged hospitalization, health inequities

Sources: *[12, 13, 17]*

Resilience Strategies for Surgical Health Systems

Strengthening the resilience of surgical health systems has become a global priority as climate change increasingly threatens the continuity, safety, and sustainability of surgical care. Resilience extends beyond disaster response to encompass the capacity of surgical systems to anticipate, adapt to, recover from, and learn from climate-related shocks while maintaining essential services [12]. Effective resilience strategies, therefore, require coordinated investments across infrastructure, resource management, workforce development, governance, and digital innovation to ensure that surgical care remains accessible, efficient, and environmentally sustainable [23]. These strategies should be integrated into routine health system planning rather than implemented solely during emergencies.

Figure 2. Climate-resilient health systems framework and its application to surgical care. The framework illustrates how integrating climate resilience across key health-system building blocks strengthens preparedness, adaptive capacity, and continuity of surgical services under climate-related disruptions.

Source: *[24]*

Climate-Resilient Infrastructure

Climate-resilient infrastructure forms the foundation of sustainable surgical systems. Hospitals and operating theatres should be designed or retrofitted to withstand floods, heatwaves, storms, and other climate-related hazards while maintaining uninterrupted access to electricity, water, oxygen, sterilisation facilities, and communication systems [25]. Risk-informed facility planning, renewable energy integration, redundant utility systems, and climate-sensitive engineering improve operational continuity during environmental emergencies. Incorporating climate resilience into health facility design not only minimises service disruptions but also reduces long-term operational costs and strengthens preparedness for future climate risks [2].

Sustainable Supply Chains and Resource Management

Building resilient surgical supply chains requires diversification of procurement networks, strategic stockpiling of essential supplies, local manufacturing where feasible, and environmentally sustainable resource management. Modern perioperative care depends on complex supply systems that are vulnerable to disruptions in production, transportation, and distribution caused by extreme weather events [26]. Circular economy approaches, including reusable medical devices where appropriate, waste reduction, recycling, and environmentally responsible procurement, can simultaneously improve supply security and reduce the environmental footprint of surgical services [22]. Healthcare organisations should also implement evidence-based sustainability initiatives that optimise energy consumption, reduce unnecessary resource use, and strengthen operational resilience across the perioperative pathway [23]. Digital technologies such as artificial intelligence, blockchain, and predictive analytics further enhance supply-chain visibility and resilience by supporting inventory management and disruption forecasting.

Workforce Preparedness and Emergency Planning

A resilient surgical workforce is essential for maintaining service continuity during climate-related emergencies. Continuous education on climate-sensitive healthcare, disaster medicine, emergency surgery, infection prevention, and occupational safety enhances the capacity of healthcare professionals to respond effectively to evolving environmental threats [27]. Regular simulation exercises, multidisciplinary emergency planning, surge-capacity development, and psychosocial support improve institutional readiness while reducing burnout during prolonged crises. Adaptive workforce planning that incorporates flexible staffing models and cross-disciplinary collaboration further strengthens the ability of surgical services to maintain essential care during periods of increased demand [5]. These approaches promote organisational learning and enhance the long-term adaptive capacity of surgical health systems.

Policy, Governance, and Financing

Effective governance provides the institutional framework necessary for implementing climate resilience across surgical health systems. National surgical policies should integrate climate adaptation into infrastructure planning, workforce development, procurement strategies, emergency preparedness, and quality improvement initiatives [7]. Cross-sector collaboration among governments, healthcare institutions, environmental agencies, and professional organisations facilitates coordinated responses to climate-related challenges while promoting evidence-informed decision-making. Sustainable financing mechanisms are equally important for supporting infrastructure modernisation, resilient technologies, workforce training, and research that strengthen long-term system performance. Embedding climate resilience within broader health system governance ensures that adaptation efforts remain coordinated, equitable, and sustainable over time [21].

Digital Health and Innovation

Digital transformation offers significant opportunities to strengthen the resilience of surgical health systems. Telemedicine, electronic health records, artificial intelligence, remote patient monitoring, predictive analytics, and interoperable health information systems improve communication, surveillance, clinical decision-making, and continuity of care during environmental disruptions [22]. Digital early-warning systems and climate-informed surveillance platforms can support proactive planning by identifying emerging risks and optimising resource allocation before disasters occur. Innovative technologies also facilitate remote education, multidisciplinary collaboration, and real-time coordination of emergency surgical services across geographically dispersed facilities. When integrated with resilient governance and sustainable infrastructure, digital innovation enhances the adaptability, efficiency, and responsiveness of surgical health systems while supporting long-term climate resilience and high-quality patient care.

Table 2: Key resilience strategies for strengthening surgical health systems under climate change

Resilience Domain	Key Strategy	Expected Outcomes
Climate-resilient infrastructure	Climate-proof facility design, backup energy and water systems	Continuity of surgical services
Sustainable supply chains	Diversified procurement, local sourcing, circular resource use	Reduced shortages and operational disruptions
Workforce preparedness	Climate education, simulation training, emergency planning	Improved emergency response and workforce resilience
Policy, governance and financing	Climate-integrated surgical policies, sustainable financing	Stronger preparedness and long-term adaptation
Digital health and innovation	Telemedicine, electronic health records, predictive analytics	Better coordination, surveillance, and decision-making

Future Perspectives

The future of surgical health systems will depend on their ability to integrate technological innovation with climate resilience to ensure safe, efficient, and sustainable surgical care. Advances in digital surgery are transforming perioperative practice through the integration of intelligent technologies that improve clinical decision-making, workflow efficiency, and system adaptability [27]. Artificial intelligence is expected to further strengthen surgical resilience by supporting predictive risk assessment, optimising operating room scheduling, enhancing resource allocation, and facilitating rapid responses during climate-related emergencies [24]. Likewise, digital twin technology offers promising opportunities to simulate hospital operations, evaluate disaster scenarios, and guide evidence-based planning for resilient surgical systems before disruptions occur [15].

Continued progress in robot-assisted minimally invasive surgery may also improve procedural precision, reduce resource utilisation, shorten recovery times, and enhance healthcare efficiency, thereby contributing to more sustainable surgical services [7]. These emerging technologies should be integrated with climate-resilient health facilities, environmentally responsible perioperative practices, and sustainable health-system design to maximise both operational resilience and environmental sustainability [8, 9].

Future research should prioritise high-quality evidence that supports the implementation, evaluation, and scaling of climate adaptation strategies specifically for surgical care. Important research areas include climate-resilient operating theatre design, sustainable perioperative technologies, low-carbon surgical pathways, intelligent supply chain management, and digital decision-support systems that enhance preparedness and continuity of care.

Equally important is the development of standardised indicators for measuring surgical resilience, environmental performance, and health-system adaptability across diverse healthcare settings. International collaboration among governments, academic institutions, professional societies, funding agencies, and global surgery networks will be essential for accelerating innovation, promoting equitable technology transfer, and strengthening research capacity, particularly in low- and middle-income countries. Sustainable procurement, resource-efficient surgical practices, and evidence-based environmental stewardship should remain central priorities for future surgical policy and practice [10, 15]. Ultimately, translating research evidence into coordinated policies and clinical practice will require sustained investment, interdisciplinary partnerships, and global knowledge sharing to build surgical health systems that are resilient, environmentally sustainable, and capable of delivering high-quality care under an increasingly changing climate [2].

Conclusion

Climate change presents an escalating challenge to surgical health systems by disrupting infrastructure, resources, workforce capacity, and the continuity of surgical care. Building resilient surgical systems requires coordinated investments in climate-resilient infrastructure, sustainable resource management, workforce preparedness, effective governance, and digital innovation. Integrating these strategies into national surgical planning and routine healthcare delivery will strengthen adaptive capacity, safeguard patient outcomes, and promote environmentally sustainable surgical services. Continued innovation, interdisciplinary collaboration, and long-term commitment are essential to ensuring that surgical health systems remain resilient and capable of delivering safe, equitable, and high-quality care in an increasingly climate-affected world.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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