

From Resilience to Anti-Fragility A Contingency-Based Supply-Chain Framework for Medical Waste Management in Resource-Constrained Healthcare Systems

Nazir Imran¹, Prof. Dr. Sarwar M. Azhar², Ms. Aisha Nazir³

¹ Ph.D. Scholar (Management Sciences), Lahore Business School, The University of Lahore, Punjab, Pakistan. Corresponding Author's Email: 70144971@student.uol.edu.pk

² Ph.D. (Management Sciences), Professor Lahore Business School, The University of Lahore, Punjab, Pakistan. Email: sarwar.azhar0309@gmail.com

³ MS IT, Lecturer University of Punjab, Jhelum Campus, Punjab, Pakistan.
Email: Aishanazir482@gmail.com

DOI: <https://doi.org/10.70670/sra.v4i2.2316>

Abstract

Medical-waste value chains in resource-poor healthcare systems are often strained due to poor segregation practices, centralized treatment facilities, poor transport controls, undefined roles of various stakeholders, lower infrastructure capabilities, non-compliance to regulations, and lack of operational data. There is a focus on building up resistance, recovery and restoration following disturbance in conventional supply-chain resilience but may not be sufficient for systems that face shocks and have a certain chronic institutional fragility. Contingency-based antifragile supply chain framework for medical-waste management by integrating Supply Chain Risk Mitigation, Resilience theory, Antifragility, Contingency theory, Dynamic capabilities, Decentralization, Real-time monitoring and Post shock learning. The aim of framework is to be further qualitatively validated of selected public and private hospitals in metro and sub-urban Punjab, Pakistan. It suggests that the systems of healthcare waste can be antifragile through being able to leverage information induced by disruption to increase their level of segregation, coordination, traceability, continuity of treatment, regulatory performance, etc. AI, IoT, RFID, blockchain and decentralized processing units aren't considered one size fits all. AI, IoT, RFID, blockchain and decentralized processing units are regarded as contingent enablers instead of universally applicable solutions. Effectiveness is a function of hospital size, geography, quantity of waste, readiness to digitalize, infrastructure, capacity of stakeholders, and regulatory enforcement. This article makes a further application in the field of supply chain theory that can be used to transcend recovery and push towards improvement in the face of volatility and provide a contextually grounded framework for designing medical-waste systems that are environmentally sustainable, technologically capable, and socially inclusive.

Keywords: Medical Waste Management; Anti-fragile Supply Chain; Supply-Chain Risk Management; Contingency Theory; Healthcare Sustainability; Digital Technologies; Resource-Constrained Healthcare Systems.

Introduction

Although healthcare systems save human lives, they also contribute huge environmental and health risks due to their energy consumption, pollution caused by pharmaceuticals or due to greenhouse-gas emissions, disposable products and hazardous waste. The health care sector can impact the environment in ways beyond the hospital building, such as direct environmental effects from purchasing, moving, treating and disposing of waste. It is particularly important in the treatment and disposal of medical waste because if segregation and disposal are not carried out properly, it could result in infectious, chemical, pharmaceutical and physical risks to medical

staff, waste handlers, local communities, soil, water and air (Karliner et al., 2020; Lenzen et al., 2020; MacNeill et al., 2021).

The management of medical-waste is a process dependent on medical-waste generation and segregation, inwards collection, temporary storage, transport, treatment and recycling (if possible) and finally disposal (World Health Organization, 2014; International Committee of the Red Cross, 2011).

Failure at any point in the chain may result in risk in the entire chain. Improper segregation can lead to increased amounts of hazardous waste, but inadequate storage can lead to high exposure). Unobserved transportation allows potentially for leakage or diversion and hazardous waste treatment, as well as its uncontrolled burning, results in transfer of health risks to the surrounding communities (Windfeld & Brooks, 2015).

Any medical-waste management should, therefore, be viewed as more of a supply-chain issue than just a narrowly technical disposal process. This is even more challenging in low resourced health systems. Hospitals might be low-budget, under-trained, have substandard treatment equipment, limited space for storage, outdated manual record-keeping systems, and nonstandard contractor supervision. Private hospitals may also be more flexible in procuring, have different accountability mechanism, generate a higher volume of waste, have more technological capacity and treatment facilities than public hospitals. This means that it is unlikely that a “standard” will be applicable in all facilities (Ali et al., 2017; Khan et al., 2019; Zamani et al., 2021).

The evidence from Pakistan points towards an ongoing lack of segregation, collection, transportation, treatment, documentation, occupational protection, and following of established rules in handling waste in hospitals. Studies indicate that there is a difference in the quality of public and private facilities, deficiency of staff knowledge, inadequate implementation, unhygienic handling and inadequate institutional monitoring (Ali et al., 2016); Ashraf et al., 2016).

Despite the fact that there are no national or provincial rules in place in certain instances, it is likely that the reason of failure to implement rules is not because they are not there but because of the poor coordination of agencies and scarcity of resources (Panezai et al., 2023; Riaz et al., 2023).

COVID-19 revealed the shortcomings of medical-waste solutions as the demand for disposable healthcare goods such as masks, gloves, testing materials, syringes, intake packaging and much more rose as a result of the pandemic (World Health Organization, 2020).

The results showed that a system that is normal when operated in certain conditions, can be overloaded when high speed changes in waste discharged, potential contamination, and transportation demand. It also highlighted the key role flexible processes, up-to-the-minute information, workplace safety and continuity of treatment play in times of disruption (Rahayu et al., 2021; Wiratsudakul et al., 2024).

The traditional Supply Chain Risk Management is a process of identifying risks, understanding vulnerabilities and creating mitigation plans. Supply-chain resilience goes a step further than this, in that it requires preparation, response, recovery and return to normal. Such views are useful, but often presume the goal of success is to get the system back to baseline. If a medical-waste system has been historically low performing at the point, reverting to the old way may very well result in unsafe and inefficient medical-waste practices again (Ponomarov & Holcomb, 2009; Pettit et al., 2010; Lavastre et al., 2014).

Another way to think about it is proposed by what is called the theory of ‘antifragility’. The antifragile system not only survives volatility, but also harnesses it to strengthen and enhance the system's future performance by leveraging the information and insights gained from the stressors, errors, variability and disruption (Taleb, 2012; Taleb, 2013).

In the context of medical-waste management, a situation that results in a medical-waste failure to the treatment process, in the transportation process, or when waste is mistakenly separated with a different bin, or more waste is added, would mean that there is a learning process, a redesign of the process, and not just a temporary recovery (Taleb & Douady, 2012; Axenie et al., 2024).

But there can be no universal template for how antifragility is to be translated into an organisation. Technical feasibility and institutional sustainability of interventions depends on hospital size, geographic location, waste amounts, facilities, literacy around information technology, budget, regulatory capacity, and relations with stakeholders (Lawrence & Lorsch, 1967).

Contingency theory is therefore needed, as it is about the relationship of organizational arrangements and environmental conditions and how that determines system performance. Digital technology have the potential to enhance this 'fit' when they are chosen to address particular operating issues (Donaldson, 2001; Le et al., 2022).

Artificial Intelligence can be used to assist in segregation using images and determining the amount of waste in the bin . RFID helps in better identification and in making better track of the waste transportation . The IoT sensors can be used to send real-time information on the conditions of the bin, its temperature, the storage conditions, or the performance of the equipment. There is a need for infrastructure, maintenance, interoperability, training, governance, and data reliable to these technologies as well . How much they are valued in this context can be either automatic or contingent (Rahayu et al., 2021).

In this article, we suggest an anti-fragile supply-chain approach for medical-waste management that relies on the resources of healthcare systems. It focuses on three objectives: Identifying vulnerabilities during the procedure, and within stakeholders; The push towards being anti-fragile, through the lens of SCRM and principles of resilience; The contingency of decentralized treatment, AI, IoT, RFID and blockchain.(Mohamed et al., 2023; Mohamed et al., 2024).

The framework that would be designed would be used for qualitative validation with the comparative hospital cases in Punjab metro and Sub-urban. The research questions of the article are:

- What are the inefficiencies in the functions of the hospital wastes system in the metropolitan and sub-urban area of Punjab and what role could stakeholder and regulatory policies play in making the system more efficient?
- How to implement decentralized waste disposal, real time monitoring and post-shock learning in a medical-waste system and how can Supply Chain Risk Management be the foundation for the medical-waste system to become anti-fragile?
- What value do decentralised processing units offer, will AI and digitization be able to enhance segregation and could RFID enhance transport monitoring?

Research Problem and Gap

Although the issue of healthcare waste management is attracting increased attention, research so far has tended to be concentrated on issues of regulatory non-compliance, operational inefficiencies, environmental risks and resilience-based responses. A focus on resilience, however, has been largely overlooked in the context of medical-waste systems in resource-limited healthcare settings, where the capacity for learning, adaptation and improvement also known as antifragility has yet to be recognized. The literature lacks the explanation of how the concept of supply-chain risk management, decentralization, post-shock learning and digital technologies including Artificial Intelligence, Internet of Things, RFID and Blockchain can be linked to a context-sensitive conceptual framework for medical-waste management. It results in a clear theoretical and practical divide particularly in low resource health care settings where frequent shocks, an underdeveloped coordination system and poor infrastructure require a more

adaptive and improvement-focused system design. This article fills that void by proposing a framework for the medical-waste management that is antifragile, based on contingency.

Literature Review

Medical Waste as an Interdependent Supply-Chain Problem

Different types of medical waste are infectious waste like body fluids, sharps, pathological waste, pharmaceutical waste, chemicals, radioactive waste and non-hazardous waste produced during a healthcare process. The key to good management is to have proper segregation as hazardous and non-hazardous waste streams need to be handled, treated and disposed of differently. The problem with poor segregation is that it makes treatment less efficient, and expands the volume that is considered hazardous (Attrah et al., 2022).

There are several stakeholders involved in the medical-waste chain: clinical staff, cleaners, waste-management team, infection-control staff, hospital administration and management, contractors, transporters, and treatment-facility operators, environmental regulators, local governments, recyclers, and surrounding communities. While actors only have a portion of control, failure in a component can have ripple effects throughout the system. This interdependence is symptomatic of what happens throughout a supply chain where inputs, outputs, people and resources need to interact in harmony in order to achieve good performance (Oliver & Webber, 1982; Cooper et al., 1997).

In resource poor environments, manual processes, and fragmented documentation are common. There is no objective way of estimating the waste volume, transport cannot be identified and treatment cannot be associated with the location of the waste production. These information gaps are what make it difficult for regulators and administrators to identify leakage, delay or mixing or unsafe diversion (Ali et al., 2017; Panezai et al., 2023).

This effect is not limited to the potential infection. Inadequately controlled incineration can result in release of harmful pollutants, whereas open dumping and unsafe recycling can lead to the transfer of harmful contaminants into soil, water bodies, consumer items and informal working areas (Singh et al., 2022; Cook et al., 2022).

Finally, sustainable medical-waste management should be realized by reducing the waste at the source, segregation, waste-safe treatment and implementation in the context of circular economy and protection of workers and communities (Wiprächtiger et al., 2021).

Medical-Waste Management in Pakistan

Formalised hospital waste regulations exist in Pakistan with responsibilities assigned in segregation, storage, collection, transportation, treatment, documentation and others. Also, there are rules in the province of Punjab. Therefore, existing instruments suggest that the key issue of policy is not just law the other is to institutionalize formal requirements into routine practices that institutions can take repeated action on. The No. of glaciers and snowfields in Pakistan are 1326 and 1567 respectively (Government of Pakistan Ministry of Environment, 2005; Government of Punjab Environmental Protection Department, 2014; Pakistan Meteorological Department, 2020).

The Pakistani study has pinpointed the need to enhance the awareness of staff, segregation practices, provision and use of protective equipment, internal transport, arrangements for the storage of waste, record keeping and treatment arrangements. There is also variation in facilities and public management versus private management. Although supporting compliance, there seems to be a relationship between compliance and organizational capacity, resources, leadership, training and enforcement based on these results. Geography also has to be taken into account on such framing and understanding of the hospital waste system in Punjab (Ali et al., 2016; Panezai et al., 2023; Ashraf et al., 2016).

Some potential problems at metropolitan hospitals are large quantities of waste, congestion, a complex network of contractors and inconsistent enforcement. At sub-urban locations, access to the treatment mechanisms might be poor, transport may be poor, equipment may not be available, and there is more involvement with informal waste handlers. These differences make it possible for a contingency approach as the same compliance requirement can force different operational configurations (Punjab Health Sector Reforms Support Project, 2013; Panezai et al., 2023).

The relationship between Pakistan's non-financial corporations' climate-related physical and transition risks and financial stability is moderated by their environmental, social and governance performance. The relevance of their study is the link between climate vulnerability, corporate sustainability and financial resilience in a developing country context. It reinforces the theory that organizations that are facing environmental risks and regulatory pressures need to develop adaptive governance, risk management and sustainability programme in order to be stable, compliant and able to respond effectively to environmental and regulatory risks over time (Javed & Bhutta, 2026).

Supply Chain Risk Management

SCRM aims to discover potential disruption, analyze the risk in terms of likelihood and impact and take steps to prevent, minimize, and get ready for, and recuperate from disruption. Examples of risks in medical-waste systems vary from segregation gremlins, storage overflow, vehicle failures, failures on logistical side, failure in treatment equipment, power failures, staff member absences, change in waste volume or loss of rain cover. Valuable use for SCRM, Vulnerabilities become evident before there is major harm. Risk mapping can be used to help define the critical control points and the responsibility and to develop alternative procedures (Lavastre et al., 2014; Pettit et al., 2010).

However, with static risk-management approaches which use fixed registers and fixed answers in the form of responses after disruption, risk-management can become static. In design, antifragility relies on having risk knowledge as an impetus to design continually (Fiksel et al., 2015).

From Resilience to Antifragility

"What went wrong" to "What went right" is just one step. Resilience is widely interpreted in the supply-chain context as the ability to preparedness, reaction and recovery to an acceptable level. Resilience has the attributes of flexibility, redundancy, visibility, collaboration and adaptive capacity (Ponomarov & Holcomb, 2009; Pettit et al., 2010).

These can have direct impacts on medical-waste systems because continuity of care and containment during medical crises must be maintained. Resilience does not always equal improvement however. Sometimes, the same centralized treatment program is used each failure, even if there has been no change in dependency that is contributing to the failures. Similarly, during an inspection, segregative practices may be temporarily improved and following the inspection, they revert back to segregative practices. Learning with recovery may be absent and vulnerability perpetuated (Nikookar et al., 2021; Fiksel et al., 2015).

Antifragility builds onto resilience and cultivates adaptation a positive one.. The key to making a system anti-fragile is to be subject to manageable stresses that expose its weaknesses, and stimulate information, experimentation, and future performance. The concept of antifragility in supply chains is manifested in various ways, including modularity, distributed capacities, rapid feedback, optionality, learning, and the ability to reconfigure (not restore) the chain (Nikookar et al., 2021).

The term antifragility is not synonymous with all perturbations being good, or all bad perturbations some kind of desired shocks. It implies that systems should be built to tolerate variance that can't be avoided, but at the same time, prevent errors from becoming

insurmountable. Small process deviations, near misses, equipment warnings, and transport delays in health care-waste management can all be valuable signals when documented, examined and acted upon to generate corrections (Taleb & Douady, 2012; Axenie et al., 2024).

The Contingency Theory and Contextual Fit

There is no one best organizational form under all conditions, according to contingency theory. The success of performance relies on the congruence between the features of the organization and its context which include environmental uncertainty, technology, size, structure, and interdependence. This is a key tenet of medical-waste systems, as hospitals vary widely in waste volume, complexity of clinical work, distance from treatment centers, and infrastructure and regulatory capacity (Lawrence & Lorsch, 1967; Donaldson, 2001).

In a large metropolitan teaching hospital, support for segregation, specific waste teams, digital traceability and treatment on site may be warranted. A small sub-urban hospital may need simpler technologies, sharing of treatment capacity, treatment on schedule, mobile treatment, or cluster-based treatment services (Mohamed et al., 2023).

Both facilities can have the same technological package which can lead to underuse, maintenance problems, or excessive cost. Contingency theory is also able to avoid digital determinism. The technology should be determined through a diagnosis of operational problem, institutional capacity and implementation environment. AI won't enhance their results if there are no bins, and blockchain won't fix erroneous data if it was entered at the source (Rahayu et al., 2021; Mohamed et al., 2023; Mohamed et al., 2024).

Dynamic Capabilities and Organizational Learning

Dynamic capabilities are the capabilities of organisations to sense, seize and transform resources and routines. Sensing for medical-waste management involves identification of change in waste volume, failure to separate waste properly, failure to transport waste by the scheduled time, or failure to treat waste properly. Seizing means making a decision on a response and transforming means changing procedures, roles, technology or infrastructure. That's what an antifragile system needs; otherwise, information can't derive improvement. Hospitals need to have authority, resources, leadership and learning processes that turn information into action. By conducting after-action reviews, incident analysis, revising standard operating procedures, soliciting staff input and engaging in across-the-board learning from facilities, institutional memory can be built. Other than physical technologies, resource-based theory also implies that organizational resources, for example, trained personnel, routine, trust among users and beneficiaries as well as learning, are also important drivers behind sustained performance. These resources are critical to the success and sustainability of making digital tools core capabilities instead of "pilot projects" that fizzle out (Barney, 1991; Teece, 2007).

Decentralized Processing

Centralized treatment can provide advantages from the economies of scale, technical specialization and regulation. However dependency on transportation, contractors, road access, fuel, schedules and the continued operation of a few facilities is also created. Adverse event may interrupt treatment at several hospitals. Decentralized/distributed processing can offer reduction of transport distance, storage times and improved local control and redundancy. Possible options include on-site treatment, cluster-based treatment (shared by neighbors) or mobile units or modular systems based on the volume of waste ((International Committee of the Red Cross, 2011; World Health Organization, 2019).

These arrangements could help minimise interruption when there is transport breakdown or sudden spate of waste. Along with the benefits of decentralization, there are risks that come with it. Technical personnel, maintenance capacity, emission control, quality assurance or adequate waste may not be available in some small facilities, and it may not be sufficient to operate the

equipment efficiently. It is important, however, to not automatically consider decentralized systems as preferable in all contexts (Attrah et al., 2022; Çelik et al., 2022).

The value depends on the (nature of) waste, its size, location, support, environmental conditions and institutions competency (Erdogan & Yilmazoglu, 2021).

Digital Technologies as Contingent Enablers

AI can aid in medical-waste sorting by utilizing image recognition, automated classification, predictive analysis, and anomaly detection. It can also predict the amount of waste and aid planning for hospital storage, transportation, and treatment capacity . To support the achievements of AI, however, the key elements are the representativeness of training data, matching sensors or cameras, staff acceptance, data governance, and system upkeep . By integrating IoT technologies, real-time data on the container fill level, temperature, storage time, equipment condition and vehicle location can be provided. This visibility can help to decrease collection delays, avoid overflow, and facilitate preventive maintenance . However, in low resource areas connectivity, battery life, devices, durability, calibration, and technical support need to be taken into account (Mohamed et al., 2023; Rahayu et al., 2021).

Containers or bags can be attached to their point of origin, waste type, collection time, collector, destination, and treatment status using RFID, thereby enhancing the identification and chain of custody monitoring process . RFID can be very beneficial in areas where manual records may not be comprehensive, or where responsibility may be ambiguous once waste is removed from the hospital setting. It requires continuous tagging and scouting, data linking and enforcement. Blockchain can provide benefits in terms of transparency, where several independent organizations need to have access to a tamper-proof and shared record. It can enhance the traceability both within hospitals, contractors, treatment facilities, and regulators. However, blockchain does not ensure the accuracy of data, it only ensures that the data entered into the system is preserved. It should thus be used in conjunction with data capture and verification, good governance, and accountability in practice (Le et al., 2022).

Proposed Contingency-Based Antifragile Framework

The proposed framework consists of four connected layers:

- Contextual contingencies
- Supply-chain vulnerabilities
- Antifragile mechanisms and technological enablers
- Performance and learning outcomes

Contextual Contingencies

The first layer captures the conditions that shape intervention suitability:

Contingency	Illustrative factors
Geography	Metropolitan, sub-urban, distance from treatment facilities, road reliability
Hospital characteristics	Public/private, size, bed capacity, clinical complexity, waste volume
Institutional capacity	Leadership, staffing, training, budget, maintenance capability
Digital readiness	Connectivity, data quality, technical expertise, system interoperability
Regulatory environment	Inspection frequency, enforcement consistency, reporting requirements
Stakeholder structure	Contractors, transporters, regulators, informal actors, community exposure

These variables determine whether a hospital should use centralized treatment, decentralized capacity, manual controls, basic digital tracking, or advanced automated systems.

Supply-Chain Vulnerabilities

The second layer identifies vulnerabilities across the waste flow:

- Incorrect segregation at the point of generation
- Mixing of hazardous and non-hazardous waste
- Inadequate containers or labelling
- Unprotected internal collection
- Excessive temporary-storage duration
- Incomplete records
- Untraceable external transportation
- Contractor non-compliance
- Treatment-equipment failure
- Unsafe recycling or diversion
- Open dumping or burning
- Weak feedback after incidents

Antifragile Mechanisms

The framework proposes three principal antifragile mechanisms.

- **Decentralization.** Reducing dependence on a single treatment facility, transporter or disposal pathway is called decentralisation. This can include one or more of the following: modular treatment, shared treatment facility cluster, backup contracts, alternate routes, or distributed storage and treatment plant capacity.

- **Real-Time Data.** Real time data enhance the visibility of processes of generation, segregation, storage, transport, treatment and disposal. This information can be generated via digital scales, IoT sensors, RFID, the classification with the help of AI, the electronic signing of manifests, or blockchain trading records.
- **Post-Shock Learning.** Post-shock learning turns incident to system improvements. Structured review of procedures, risk maps, retraining staff and reallocating resources should be conducted as a response to near misses, treatment failures, delays in collecting wastes, outbreaks of disease, and sudden wastes surges.

Antifragile Outcomes

The intended outcomes are:

- Improved segregation accuracy
- Reduced hazardous-waste volume
- Greater traceability
- Shorter storage duration
- Reduced transport dependency
- Faster detection of failure
- Improved regulatory compliance
- Enhanced occupational safety
- Reduced environmental leakage
- Stronger institutional learning
- Better performance during future shocks

The present study proposes a conceptual framework and propositions. The present study proposes a conceptual framework and propositions.

Theoretical Propositions

- **Proposition 1:** Fragmented coordination of stakeholders is a stronger driver of failures in medical-waste collection and disposal than the lack of formal medical-waste regulations in resource-constrained health-care systems.
- **Proposition 2:** Supply Chain Risk Management is the diagnostic base for antifragility, yet it is effective just when there's a connection between risk identification and feedback, adaptation, and procedural redesign.
- **Proposition 3:** Resilience capacities are vital to continuity and recovery, but only when disruption leads to measurable gains in future procedures and performance is a system antifragile.
- **Proposition 4:** The geographical, volume, transport, institutional, environmental and maintenance factors affect decentralized treatment effectiveness.
- **Proposition 5:** AI, IoT, RFID, and blockchain can enhance the performance of medical waste only when they are paired with a specific problem in the process, and when they are backed by sufficient institutional readiness.
- **Proposition 6:** The following preconditions are important in the context of successful technological implementation, Staff competence, role clarity, segregation infrastructure, data quality, maintenance capacity, financial viability and regulatory support are preconditions.

- **Proposition 7:** Resilient healthcare institutions are more likely to become antifragile institutions when they assess incidents systematically, adjust processes, retrain personnel, and reorganize resources following disruption.

The propositions that are drawn from these concepts are then tested empirically using comparative case studies of public and private hospitals in metropolitan and suburban areas of Punjab.

Framework of Antifragile Medical-Waste Management

This study suggests a framework for the shift from traditional resilience to antifragility in medical-waste management systems in resource-poor health-care environments. Resilience helps a system to anticipate disruption, sustain critical functions, and rebound to an acceptable level. Antifragility is a further aspect of this ability, as it allows the system to learn from failures, adjust the procedures and enhance the performance in the future. The framework starts with contextual contingencies – hospital size, public or private ownership, metropolitan versus suburban location, waste volume, clinical complexity, infrastructure, digital readiness, capacity of stakeholders, and regulatory enforcement. These factors affect vulnerabilities of the medical-waste chain as well as appropriateness of interventions available. As such, there is no universal 'one-size-fits-all' organizational structure, technology or treatment solution. The second component is vulnerabilities in the supply chain from waste generation to segregation, to internal collection and storage, to transportation, waste treatment, and recycling and waste disposal. Common weaknesses are lack of segregation, lack of container security, too long storage period, lack of documentation, contractor compliance, lack of transportation traceability, failure of treatment equipment, unsafe recycling, and lack of institutional feedback. The stages are linked and failure in one stage can raise risks to occupational, environmental, and regulatory health at many other stages. Third and final, there are the antifragile mechanisms. The diagnostic foundation is achieved through Supply Chain Risk Management, which identifies hazards, vulnerabilities, critical control points and alternative response. Resilience capabilities including flexibility, redundancy, visibility, and collaboration – contribute to the continuity during a disruption. The road to antifragility, however, goes through three other mechanisms: decentralization, real-time information and post-shock learning. Decentralizing minimizes over-reliance on one treatment facility, transporter, route or disposal pathway. The type of treatment can vary from on site treatment, cluster based facilities, mobile facilities, alternative transportation and modular processing. Digital scales, electronic manifests, Internet of Things (IoT) sensors, Radio Frequency Identification (RFID) tracking, AI-powered segregation, and blockchain based records help increase visibility in real time. Post-shock learning translates incidents, near misses, transport delays, segregation failures, and waste surges into new procedures, new risk maps, new staff training, and reallocating resources. Digital technologies are considered as means to an end not all the time. AI can help with segregation and forecasting, IoT can help with storage, equipment and vehicle conditions, RFID can help with identification and chain of custody and blockchain can help with inter-organizational traceability. They work best when they are process-disciplined, staff-capable, data quality, connected, maintained, cost effective, and accepted by regulators. If the context, capacity and technology are well matched, the framework predicts better segregation, less hazardous waste, better traceability, less time in storage, safer transport, better compliance with regulations, less leakage into the environment, better protection for employees and better learning post-disruption.

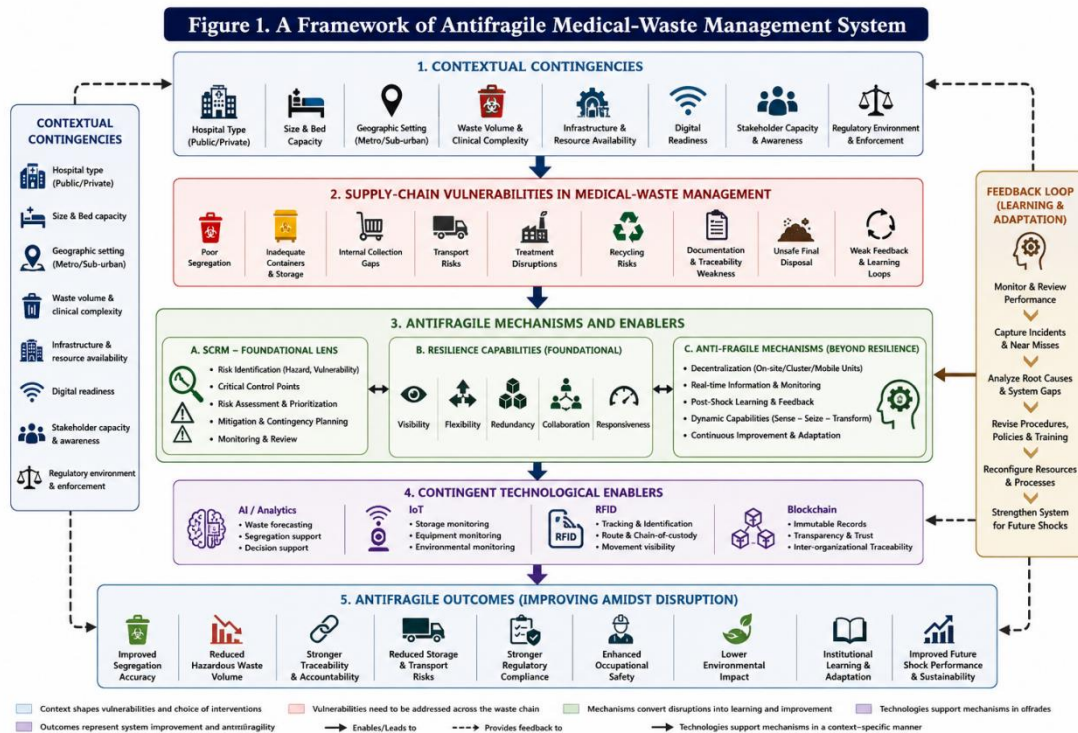


Figure-1: A Framework of Antifragile Medical-Waste Management System

Research Approach and Conceptual Development Method

Research Design

The concept paper design and integrative literature review are used for this article. It does not present new empirical information, and is not qualitative research, or an empirical investigation. The article, however, consolidates theoretical, empirical, policy, and institutional literature to create a contingency-based approach to be used for antifragile management of medical waste in resource-poor health care systems. A conceptual-paper approach is suitable given that the key goal of the study is to connect previously disparate bodies of knowledge, clarify theoretical relationships, and develop a new theoretical framework and propositions that will be empirically examined in the future. This article brings together views from the fields of Supply Chain Risk Management, supply-chain resilience, the antifragility concept, the contingency theory, dynamic capabilities, decentralization, organizational learning and digital traceability. These viewpoints are integrated into a framework of understanding how medical-waste systems can shift from recovery to learning, adapting and improving in the face of disruption.

Integrative Literature Review

This study takes an integrative approach grounded in extant literature, reviewed critically and cogently. With the purpose to synthesize information from a variety of disciplines and types of sources to gain a comprehensive theoretical framework, thus an integrative review fits appropriately. A literature review explores medical-waste management from the perspective of healthcare sustainability, environmental management, supply-chain risk, resilience, antifragility, organizational theory, digital technology, and public regulation. The review is largely based on journal articles (peer-reviewed), scholarly books, institutional reports, government regulations, international guidelines and relevant policy documents. Medical-waste processes and their regulatory environment, technological solutions and constraints of healthcare systems are understood from sources within the World Health Organization, the International Committee of the Red Cross, national and provincial regulatory bodies and reputable academic databases.

Thematic Areas

The literature was reviewed on the following themes:

- Medical waste management as an interdependent problem in supply chain.
- Implementation of medical-waste regulation in Pakistan appears to be lacking.
- SC risk management and vulnerability identification.
- The change from resilience to antifragility.
- Contingency theory and context–intervention alignment.
- Dynamic capabilities and organizational learning.
- Treatment in central or decentralized treatment facilities.
- Contingent technological enablers: AI, IoT, RFID and Blockchain.
- Occupational/ environmental and social aspects of medical-waste management.

The themes were chosen as they are directly related to the development of the proposed framework.

Literature Selection and Synthesis

The literature is purposively selected so that the articles are relevant to the conceptual goals of the article. Sources were selected that:

- Discussed medical-waste generation, segregation, collection, storage, transport, treatment and disposal;
- Used knowledge-based evidence to assess the gaps in resource-limited health care settings;
- Established risk, resilience, adaptation and antifragility principles in the supply chain;
- Examine organizational fit, dynamic capabilities, or institutional learning;
- Assessed decentralized waste-treatment arrangements;
- Reviewed the possibilities of using AI, IoT, RFID, blockchain or real-time monitoring; took into account the regulatory and healthcare landscape in Pakistan;
- Provided authoritative international standards or guidance.

Sources were eliminated when they were not related to the conceptual variables, could not be identified as being authored by an individual or institution, duplicated existing sources, and did not help in development of the framework. The literature selected was not analysed as a data set for statistical aggregation. However, it was analyzed using thematic conceptual synthesis. The literature was scanned for concepts, mechanisms, contextual factors, and outcomes that were anticipated; they were subsequently synthesized into a logical theoretical framework.

Nature of Propositions

The propositions stated in this article are theory-based statements, based on existing literature. They're not conclusions drawn from an experiment. They are there to describe the anticipated relationships and serve as a basis for further validation. For instance, the article suggests that the non-compliance issue could be more of a fragmented stakeholder coordination problem than a problem with regulations, that resilience is not enough for antifragility, that decentralization is a good thing only under certain situational conditions, and that digital technologies can enhance performance only when accompanied by the institutional capacity and the specific problem of processes.

These propositions can be further elaborated, reinforced, changed and discarded by empirical investigation.

Framework Development

The framework has been developed in four phases.

- The literature was reviewed to identify the key vulnerabilities in the medical-waste supply chain, such as inadequate segregation, incomplete documentation, inadequate storage, reliance on transport, inadequate compliance by contractors, inability to treat wastes and weak learning after the incident.
- Secondly, appropriate theoretical frameworks were contrasted. An explanation of risk identification and risk mitigation was provided using the lens of Supply Chain Risk Management, an explanation on continuity and recovery was provided using the lens of resilience theory, an explanation on learning and improving under disruption was provided using the lens of the antifragility theory, an explanation on intervention matching to context was provided using the lens of the contingency theory, and an explanation on how organizations sense, respond and transform in the face of changing conditions was provided using the lens of dynamic-capabilities theory.
- Third, organizational and technological mechanisms were incorporated in the framework. These included decentralization, real time monitoring, post-shock learning, AI assisted segregation, IoT based monitoring, RFID based traceability and inter organisational records supported by blockchain.
- Fourth, the linkages between contextual contingencies, vulnerabilities in the supply chain, antifragile mechanisms, technological enablers and expected outcomes were formulated in the form of theoretical propositions. These propositions are not given as findings but as hypotheses for subsequent empirical tests.

Contribution of the Conceptual Approach

The main contribution of the article is bringing together the various theoretical perspectives in one package: Antifragile Medical-waste Management. Earlier research often focusses on one of the following aspects of waste regulation, hospital practices, risks in supply chains, resilience, digital technology, separately. The present conceptual synthesis describes the interplay and the impact on the effectiveness of these elements, based on the hospital characteristics, geography, waste volume, infrastructure, digital readiness, capacity of stakeholders and regulatory enforcement.

The article makes a contribution in terms of:

- Thinking of medical-waste management as part of an organizational supply chain;
- Uncovering the meaning of the word "antifragile" and the difference between it and resilience;
- Nurturing decentralization, as an antifragile mechanism, real-time information, and post-shock learning;
- Using digital technologies as provisional, not universal, solutions;
- Formulating ideas for future empirical investigation; and
- Offering a framework which can be used to guide comparative research in public and private healthcare facilities.

Future Empirical Validation

The framework has not been tested in practice at this point. It can be explored in a future study using multiple case study approach with selected hospitals in public and private sector in metropolitan and suburban areas of Pakistan. To evaluate the proposed relationships in practice, interviews, observations, institutional records and policy documents might be used. The future

empirical study would not only confirm the framework, but would lead to develop theory. It would explore the operations of the proposed mechanisms in different institutional, geographical and technological settings and might end up with the modification, extension or rejection of any of the propositions. Moreover, future research may validate the antifragility concept in the field of medical waste management as well as supply chain management.

Discussion

Theoretical Contribution

The framework expands medical-waste research by considering the overall management of waste as an inter-organizational supply chain, one comprised of a sequence of one-off hospital responsibilities. This vision highlights all the material, informational, contractual and regulatory relationships between waste generators, transport operators, treatment facility operators, regulators and communities. The article makes a distinction between resilience and antifragility. The difference between resilience and antifragility has to do with the fact that resilience caters to continuity of services, whereas antifragility is based on learning to increase performance later on. It is important to remember that repeated recovery, without redesign, can give a false sense of safety. The framework that has been made is based on contingency theory and it does not tell a universal prescription. It states that decentralization, AI, IoT, RFID or blockchain is what works for the hospital as each has distinct pros and cons. The framework goes on correlating antifragility and dynamic capabilities, as well. Done well, organizational processes of real-time sensing, rapid response, and procedural transformation can all convert disruption-generated information into improved performance.

Practical Implications

The first step should not be purchasing technology but process mapping, which should be completed by hospital administrators. All links in the waste chain need to be examined, including any potential gaps for responsibility, delays, loss of information, risk of exposure and reliance on third parties. Prior to the introduction of advanced digital tools, simple segregation, containers, labeling, staff training, protective equipment, and accountability should be set up. Technology ought to improve an existing process not disguise its lack. Furthermore, if the hospital is far away from acceptable treatment facility to consider centralized transporting then compare with on site, cluster or mobile treatment. Considerations should include capital cost, maintenance, environmental performance, capacities, staff competence, and regulatory approval. Where measurable gains can be obtained, by implementing AI segregation first, you should do it in the high volume/high error places. RFID or IoT tracking should be a first priority where transportation, or transportation contractor accountability, is weak. From periodic inspections to risk-based, data-supported oversight. Clear definitions of data quality and data access responsibilities, combined with a digital manifest, treatment confirmation, incident alerts, and facility-level performance indicators, can strengthen enforcement.

Social Inclusion

People with weak organizational capacities such as cleaners, handlers and transporters of medical waste and informal recyclers are often impacted by the medical-waste system. These groups should not be blamed for shifting the risk so to be anti-fragile.

This socially inclusive approach should include protecting the occupation, training, vaccinating if appropriate, reporting, and formal involvement of workers, who know how things practically work. Informal actors must not be excluded from system design as this exclusion without alternate livelihoods may push unsafe activity further under cover.

Environmental Sustainability

An antifragile system should minimize the impact that it would have on the environment, not just preserve the continuity of disposal. This can also help make better segregation of the material,

which can decrease the material that needs costly and energy consuming treatment, and enable the safe recycling of materials toward to resource efficiency. Emissions, energy demand, waste composition, scale and capacity of maintenance should be taken into consideration when selecting a treatment method. An over-technological system which cannot be safely manipulated or locally maintained can be less sustainable than a simpler context appropriate alternative system.

Policy Implications

- The first is to target implementation strategies on issues of coordination and accountability and not assume that more rules are the solution. The responsibilities should be mapped for the various departments such as health departments, environmental agencies, hospitals, contractors, local government agencies.
- Second, models of implementation should be allowed to vary across the provinces. Operational pathways, including common safety outcomes should be utilized in response to the differing resources available at metropolitan teaching hospitals, district hospitals, private facilities and sub-urban centres.
- Thirdly, digital traceability standards shall be based on interoperability and proportionality. It is important not to exclude small facilities for lack of access to complex platforms. A hierarchical system, which utilizes anything from a common electronic logbook to RFID or blockchain-based networks, might be more feasible.
- Fourth, ensure that procurement policies consider things other than initial purchase price, such as lifecycle cost, maintenance, training, vendor support, data ownership and interoperability.
- Fifth, regulators should ensure learning can take place with non-punitive reporting of near misses and operational failures, whilst retaining penalties for deliberate dumping, falsifying records, and/or unsafe diversion.

Limitations and Future Research

- Conceptually, the proposed framework is still underdeveloped and needs to be validated with research. It may be applicable in various ways to different healthcare systems with varying regulations, economics, and cultures.
- The intended qualitative study is with six hospitals, for analytic and not for statistical generalization. The framework needs to be tested on a broader range of facilities and provinces in the future.
- Quantitative studies might be able to quantify the anti-fragility of an individual, such as: efficiency of improvement after disruption, less recovery time, more learning frequencies, more diverse treatment pathways, and changes of segregation accuracy.
- Additionally, given the untested cost-effectiveness of supporting technology like AI, RFID, IoT, and decentralized treatment, future research should involve piloting interventions and longitudinal design.
- Informal waste actors need to be investigated in more detail. Further research on how to integrate formalization, protection of occupations, circular economy, and alternative livelihoods in ways that do not deepen social exclusion should be conducted.

Conclusions

In resource constrained healthcare systems, medical-waste management efforts are more than a checklist of items to be complied or provisions of central disposal or temporary recovery following disruption. It needs a supply-chain approach — an interdependence between segregation, storage, transport, treatment, regulation, information and stakeholder behaviour. Conventional SCRM and resilience are core tools that help you to provide the foundations for

identifying risk, maintaining continuity and restoring capability. They are not adequate, however, if the systems frequently go back to unsafe or inefficient operating conditions. Antifragility offers a more powerful goal: harnessing disorder to aid in the design of future performance. Within the proposed framework, the practice of antifragility is translated into risk decentralization, real-time data, learning after a shock and the ability to reconfigure procedures and resources. These mechanisms are matched to context due to Contingency theory. AI or IoT or RFID or blockchain or decentralized processing is not a panacea! Their effectiveness relies on their geographical location, size of the hospital, amount of waste materials, digital readiness, institutional capability, coordination of stakeholders, and regulatory enforcement. Thus, it calls for a shift from technology-oriented intervention to problem-oriented configuration. The key is not only surviving disruption but, changing healthcare systems into safer, more sustainable and more capable due to what they have learned from the volatility, and this can be done by proper implementation of contextual diagnosis, supply-chain risk management, adaptive capacity and institutional learning.

Recommendations/ Technology-Based Solutions; Adaptable from Developed Healthcare Systems

Not only can the practices of digitisation, traceability and monitoring in developed countries be appreciated, but they also can be transferred to resource-constrained countries for their healthcare systems. But such solutions need not be exported as "turnkey packages". Their adoption rate should be step-by-step and should go hand in hand with the size of the hospital, amount of waste, the infrastructure, ability of the employees, regulatory capabilities and financial resources. The following technologies can help pave the way from the fragmented, reactive approach of medical-waste management toward a more visible, accountable and learning-focused system.

Electronic Waste-Manifest System

A digital record of waste generation, collection, transportation, final disposal, and treatment can replace the disjointed paper records in an electronic waste-manifest system. The United States Environmental Protection Agency has an electronic manifest system for waste generators, transporters, receiving facilities and regulators to create, sign, correct, and view records of shipments. Such a system could be extended to medical waste management in Pakistan, with all actors involved in medical waste management such as hospitals, contractors, transporters, treatment systems, and environmental regulators—linked via a common platform.

An individual identification number should be assigned to each consignment and include details of the origin of the waste, its type, quantity, collection date, the persons collecting it, where it is being taken and its treatment state. This would mean better cradle to grave traceability, less manipulation of documents and enable regulators to see delayed, diverted, rejected and untreated consignment.

GPS/ GPRS-Enabled Vehicle Tracking

Medical waste carrying vehicles should be fitted with GPS devices with GPRS/ mobile data. Systems can be used to document route, location, speed, stopping time, collection schedule, arrival at an authorized treatment facility. Non-restriction of movement is a good example where geofencing could be used that may concern the presence of non-permitted vehicles at a non-permitted treatment. GPS/GPRS tracking would be particularly useful if areas of weak contractor accountability exist or hospitals are in areas distant from centralized treatment facilities. The technology ought to be linked to the electronic manifest in order to make a comparison between physical movement and documentary records. For areas with less mobile connectivity, offline data-storage would be needed.

IoT-Enabled Smart Waste Containers

Fill levels, container opening, weight, temperature, humidity and storage time can be monitored with the IoT sensor. This data can help hospitals avoid having too many waste bins filling up, reducing storage space, potential infection hazards, and wasted collection trips. For certain waste streams, such as pathological, pharmaceutical, or other waste streams which need controlled storage, temperature sensors may be particularly useful. Warnings can be issued to waste handlers at a predetermined percentage of fullness or whenever storage conditions exceed the safety guidelines. Networked smart bins can be adopted in large hospital, or implement digital weighing scales and cheap fill level sensors in smaller ones. Therefore, IoT uptake ought to be guided by business necessity and not the latest technology.

Real-Time Waste-Control Dashboards

Flush reports of waste generated by department, segregation mistakes, waste collection delays, waste stored for long period, sudden status change of transport, no waste treated confirmation, contractor performance, incident reports should be readily present on a dashboard for hospital administrators and regulators. NHS England's clinical-waste plan focuses on better information and live systems that will enable clinical-waste consignments to be tracked from their creation to their disposal. Hospitals could have similar dashboards to facilitate evidence-based inspection and to offer the chance to compare performance by departments across different hospitals. Simple indicators to consider include kilograms of hazardous waste processed per occupied bed, percentage of waste correctly segregated, delayed collection, unconfirmed shipment, treatment plant equipment downtime and repeated violations by contractors.

Artificial Intelligence for Segregation and Forecasting

AI cameras or mobile apps could help verify what infectious is, recyclable is, pharmaceuticals, sharps, and other waste. Image recognition systems could alert immediately in the case of waste going into the wrong container. AI can also be used to predict waste volumes, collection needs, storage strain and treatment capacity for outbreaks or seasonal events based on past data. AI should be first tried on the higher quantity departments that are prone to segregating issues. It should not be a substitute for colour coded containers, staff training, supervision or responsibilities. It is reliant on locally representative training data, necessarily good cameras, staff acceptance and regular system maintenance.

Digital Treatment and Emission Monitoring

All treatment equipment should be equipped with sensors to capture treatment time, energy use, equipment failures, emission-control results, treatment temperature and pressure. Automatic records could make it easier to identify if the correct treatment has been given to each batch of waste – not just manually-completed certificates.

If an incinerator is installed, air-quality and emission sensors might aid in environmental monitoring and in the early detection of unsafe operating of the incinerator. Installed environmental sensors around healthcare waste-methodology units have proven to be useful when developed healthcare initiatives have been used for monitoring local air conditions. Instead of just collecting data, such monitoring should be tied to maintenance plans and notify regulatory bodies.

Blockchain for Shared Traceability

Blockchain can be used when multiple separate institutions need a shared and secure (tamper-evident) record. Transfers, receipts, treatments, and hospital wastes disposals can be recorded on the permissioned network by hospitals, contractors, transporters, treatment facilities, and regulators. But, fundamental digital record-keeping infrastructure, universal waste codes and other standards, accurate back desk entries, and institutional duties need to be in place before blockchain is implemented.

In fact, although blockchain stores input data, it does not ensure that the input data are true. Hence it should not be considered the entry point for digitisation but rather an advanced governance tool.

Phased Implementation

Technology adoption should follow a phased model. Adoption of technology has to be accomplished in phases:

Foundation Stage: The use of colour coding, staff training, digital weighing, standardised electronic logs and bar code identification is highlighted in the foundation stage.

Traceability Stage: electronic manifests, GPS/GPRS vehicle tracking, mobile scanning and treatment confirmation.

Monitoring Stage: IoT containers, facility dashboards, equipment sensors, and automatic incident alerts.

Advanced Stage: AI aided Segregation & Forecasting, Integrated Regulatory platforms, Permissioned blockchain records would make basic process disciplined and running in hospitals before implementing complex systems. All about enhanced visibility, responsibility, learning, safety and future performance during disruption – not about the maximum attainable digitization!

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