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Modeling the Dynamics of Post-COVID Societal Resilience: Mathematical Insights into Recovery Strategies and Adaptive Governance

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Abstract

The global outbreak of COVID-19 has presented unparalleled difficulties for societies around the globe, necessitating the development of comprehensive programmes for recovery and the implementation of adaptive governance measures. The present study work explores the use of mathematical modelling as a means to comprehend the intricacies of social resilience in the aftermath of the COVID-19 pandemic. This study focuses on the examination of recovery techniques and their implications for adaptive governance. It employs diverse mathematical methodologies to provide valuable insights into effectively traversing the intricate terrain of recovery. Utilising a multidisciplinary framework, the present study not only examines the quantitative dimensions of recovery, but also takes into account the complex socio-cultural, economic, and psychological variables that shape the trajectory towards resilience. Our objective is to get a full comprehension of the post-COVID healing process by combining mathematical models with qualitative observations. The examination of recovery pathways is enhanced by an assessment of possible policy solutions, emphasising the customization of adaptive governance to changing conditions. By using this comprehensive methodology, our aim is to provide policymakers with a resilient framework for formulating recovery plans that are both efficacious and flexible in response to the changing demands of societies as they traverse the unexplored terrain of the post-pandemic era.

Keywords: Covid, Modelling, Governance, Mathematical, Societal

Introduction

The advent of the COVID-19 pandemic signified a significant juncture in worldwide history, causing substantial disruptions to communities, economy, and everyday routines on an unparalleled magnitude (OECD, 2020). The COVID-19 pandemic has presented a range of complicated difficulties, highlighting the need of informed methods for recovery and adaptable governance systems in addressing the aftermath (Omede et al., 2023). In the context of global efforts to reconstruct and envision future trajectories, the use of mathematical modelling in conjunction with recovery techniques and adaptive governance presents a potentially fruitful approach to navigating the complex dynamics of social resilience in the aftermath of the COVID-19 pandemic.

Governments and institutions have implemented a range of recovery initiatives in response to the disruptions caused by the pandemic, with the objective of reinstating normality and promoting sustainable development (Jomo & Chowdhury, 2020). The tactics mentioned include a wide range of areas, including healthcare system improvements, economic stimulus measures, immunisation initiatives, and behavioural treatments. A thorough comprehension of the possible consequences of these efforts is essential (Ferguson et al., 2020). In addition, there has been an increased recognition of the significance of adaptive governance mechanisms among policymakers as they grapple with uncertainties and changing conditions (Biesbroek et al., 2020). Resilient societies are characterised by their capacity to successfully adapt and react, necessitating the implementation of policies that strike a balance between standardisation and flexibility (Loorbach et al., 2017).

The use of mathematical modelling has been more prominent as an effective instrument for comprehending intricate systems and providing guidance for policy-making (Ferguson et al., 2020; Koks et al., 2021). Within the framework of post-COVID recuperation, mathematical models possess the capacity to forecast trajectories of recovery, evaluate the consequences of diverse tactics, and discern possible obstacles and compromises (Chang et al., 2021). These models have the capability to provide decision-makers a solid basis for making well-informed decisions by providing evidence-based insights into the probable consequences of rehabilitation techniques.

Objectives of the Study

The objective of this research article is to provide a scholarly contribution to the ongoing discussion on societal resilience in the post-COVID era. This will be achieved by using mathematical modelling techniques to investigate various recovery tactics and their potential impact on adaptive governance. This research aims to provide insights into the complex dynamics that influence the recovery trajectory after the pandemic by examining recovery methods using mathematical frameworks. This study employs a mixed-methods approach that combines quantitative modelling and qualitative research in order to provide significant insights on effectively navigating the intricate terrain of recovery and adaptive governance.

This article will now proceed to examine the precise aims of the study, evaluate the importance of the research, outline the research technique used, provide the collected results, and provide a full analysis and discussion of the findings. Through the integration of theoretical perspectives and empirical investigation, the objective of this work is to enhance comprehension of the potential of mathematical modelling to facilitate successful recovery tactics and adaptive governance in a post-COVID era.

Significance of the Study

The study's significance lies in its potential to contribute to the existing body of knowledge in the field.

This work has substantial importance within academic, policy, and social domains. Through the integration of mathematical modelling and insights from several fields, this study makes a valuable contribution to the growth of interdisciplinary knowledge. The findings of this research have broad relevance across several domains.

The core of its value is in its capacity to provide information for the purpose of decision-making. The use of quantitative analysis to simulate different recovery options provides policymakers with a strong empirical basis for decision-making. In an environment characterised by a lack of certainty, the availability of forecasts of prospective outcomes provides decision-makers with valuable resources to make educated decisions that are in line with the particular requirements and ambitions of societies.

Furthermore, the examination of adaptive governance frameworks conducted in this paper is a significant and influential contribution. The evaluation of various governance solutions using quantitative methods provides a pragmatic framework for designing adaptable governance structures. In a dynamic context marked by rapid transformations, the capacity to promptly adjust policy becomes utmost significance. Through the process of evaluating the efficacy of various methods, this study provides policymakers with the means to develop governance solutions that are adaptable to changing conditions, therefore promoting a recovery that is both successful and efficient.

The multidisciplinary aspect of this work represents a substantial advancement in the academic debate. This statement highlights the interdependent connection between mathematical modelling and the complex socio-economic processes seen in the actual world.

The research effectively combines quantitative modelling with qualitative insights to examine the intricate nature of social resilience from many perspectives. This approach allows for a comprehensive comprehension of the subject matter that surpasses disciplinary limitations.

The ramifications of the research extend to future scenarios, therefore equipping society to navigate forthcoming uncertainty. The approaches and frameworks presented in this study demonstrate a high degree of flexibility, allowing for their use in other scenarios outside the specific circumstances of the COVID-19 crisis. As societies confront prospective future crises, equipped with the knowledge obtained from this study, they may enhance their ability to foresee, alleviate, and rebound from a diverse range of obstacles.

In summary, the importance of this work extends to several areas, including the provision of data-driven insights to decision-makers, the improvement of governance techniques, the promotion of multidisciplinary cooperation, and the cultivation of readiness for future uncertainties. In the aftermath of the COVID-19 pandemic, this study provides valuable insights into the development of resilient and adaptable cultures, offering guidance for the global recovery process.

Literature review

The COVID-19 pandemic has stimulated an unparalleled increase in study endeavours focused on comprehending and mitigating its extensive ramifications. In the present environment, there has been a growing emphasis on investigating the concept of societal resilience in the aftermath of the COVID-19 pandemic. This has become a crucial topic of scholarly inquiry, requiring an interdisciplinary methodology that combines mathematical modelling, plans for recovery, and adaptive governance mechanisms. The present literature review examines many study topics, emphasising the integration of mathematical ideas with recovery tactics and adaptive governance systems.

The use of mathematical modelling has been crucial in comprehending and forecasting the intricacies of the pandemic's behaviour. In the first stages of research, scholars used compartmental models, such as the SEIR model, to simulate the propagation of diseases and assess the possible consequences of implementing policies to mitigate their spread (Anderson et al., 2020). Nevertheless, with the transition from urgent pandemic reaction to long-term recovery, there has been an expansion in the use of mathematical modelling. Agent-based models (ABMs) have become more prominent because to their capacity to replicate individual behaviours and interactions, effectively reflecting the complex dynamics of recovery situations (Epstein et al., 2008). These models enable researchers to forecast the impacts of different recovery methods, such as vaccination campaigns, economic stimulus packages, and healthcare system improvements, providing valuable insights into their capacity to boost social resilience.

The complex and diverse character of the COVID-19 situation necessitates the implementation of extensive rehabilitation solutions. Extensive research has emphasised the significance of economic revival, fortification of the healthcare system, and implementation of social support systems as crucial factors in cultivating resilience in the aftermath of a pandemic. The need of tailored stimulus measures in mitigating the impacts of a recession and restoring economic stability is emphasised in economic recovery models (Baldwin & Weder di Mauro, 2020). Analyses of the healthcare system focus on examining strategies that promote the development of capacity to improve the delivery of healthcare services, hence assuring readiness for any future health emergencies (Dzau et al., 2020). Furthermore, scholarly research on social resilience underscores the importance of active participation within communities, provision of mental health assistance, and uninterrupted access to education as crucial factors in fostering overall societal welfare (Huremović, 2019).

Adaptive governance, which operates at the intersection of recovery and resilience, has garnered significant attention as a crucial element of post-COVID solutions. The ever-changing and dynamic character of the epidemic has emphasised the need for governance structures that can quickly and effectively adjust to shifting conditions. Fransen et al. (2022) argue that adaptive governance is characterised by the integration of data-driven decision-making, policy flexibility, and stakeholder participation as crucial components. Numerous studies have shown that the implementation of proficient governance techniques, which are guided by up-to-date data and input from stakeholders, may significantly improve the adaptability and promptness of recovery initiatives. This, in turn, contributes to the broader objective of fostering societal resilience (Fenxia, 2022).

The amalgamation of mathematical modelling with recovery solutions and adaptive governance signifies an innovative and auspicious area in post-pandemic research. In recent years, there has been a growing body of research that investigates the potential synergistic relationship between mathematical insights and the development of recovery planning strategies. For example, Acemoglu et al. (2020) used computer models to evaluate the economic consequences of various recovery methods, providing policymakers with valuable insights for effectively allocating resources. In addition, the integration of behavioural elements into mathematical models provides a more comprehensive comprehension of the impact of human decision-making on the effectiveness of rehabilitation efforts, facilitating the development of focused treatments (Ferguson et al., 2020).

An exemplary illustration of this integration may be seen in the modelling of vaccination programmes. Mathematical models have played a crucial role in forecasting the impact of vaccination rates on the comeback of diseases, offering invaluable insights for the development of public health strategies. The models under consideration take into account several parameters, including the effectiveness of vaccines, the logistical aspects of distribution, and the desire of the public to get vaccinations. These models demonstrate the intricate relationship between mathematical precision and the development of strategies for recovery (Lewnard & Lo, 2020).

Despite the increasing volume of scholarly work that investigates the intricacies of societal resilience in the aftermath of the COVID-19 pandemic, there exists a notable study deficiency in the amalgamation of mathematical modelling with recovery tactics and adaptive governance mechanisms. Although there have been several research that have examined mathematical models pertaining to the spread of diseases, economic recovery, and improvements in healthcare systems, only a limited number of these studies have effectively integrated these models with detailed recovery methods and adaptable governance frameworks. The absence of a comprehensive grasp of how mathematical insights might contribute to real-world policy choices in the post-pandemic era, especially in relation to various recovery initiatives and governance systems, is a significant obstacle. The integration of mathematical models with recovery techniques and adaptive governance may serve as a means to bridge this gap, so establishing a stronger basis for decision-making that is grounded in empirical data. This approach equips policymakers with the necessary skills to successfully manage the intricate challenges associated with societal resilience in the aftermath of the COVID-19 pandemic.

Methodology

Research Approach

The present study used a mixed-methods research approach, which integrates quantitative mathematical modelling with qualitative analysis. The objective of this study was to examine the complex relationship between recovery tactics and adaptive governance mechanisms within the unique context of post-COVID societal resilience in Pakistan. The study methodology incorporates both exploratory and explanatory components, including mathematical modelling to simulate various recovery scenarios and qualitative analysis to assess the implications for adaptive governance.

Sampling

The research aimed to examine the social resilience in certain cities of Pakistan, including Karachi, Lahore, and Islamabad, in the aftermath of the COVID-19 pandemic. The selection of these cities is based on their representation of a wide range of socio-economic origins, varying degrees of urbanisation, and distinct experiences of post-pandemic recovery. The use of purposive sampling in this study guarantees a thorough comprehension of the localised recovery dynamics inside Pakistan.

Data Collection

The process of data collecting in an academic context often entails the acquisition of quantitative data that is unique to a certain city. This data is then used to develop and fine-tune mathematical models. This encompasses a range of elements specific to each city, such as epidemiological statistics, economic indicators, healthcare system parameters, and behavioural aspects. The process of collecting qualitative data included the examination of city-specific government policies and official reports, as well as the conduction of interviews with local government officials, healthcare specialists, and community leaders. The interviews provide vital insights about the development and execution of recovery programmes and adaptive governance mechanisms that are customised to the unique circumstances of each community.

Data Analysis

The process of quantitative data analysis involved the application of mathematical model to the unique features of each city. The models provided forecasts of possible recovery paths while considering the unique dynamics of each urban area. The process of qualitative data analysis encompasses the systematic application of thematic coding to policy papers and interview transcripts. This methodology aimed to find recurrent themes and patterns pertaining to recovery efforts and adaptive governance practises within the chosen cities. The integration of quantitative and qualitative information allows for a comprehensive comprehension of recovery processes at the urban level.

The amalgamation of quantitative insights derived from mathematical modelling and qualitative research provides a holistic viewpoint on the resilience of post-COVID societies in the distinct urban areas of Karachi, Lahore, and Islamabad. The estimation of recovery paths in terms of quantity is contingent upon the specific adaptive governance frameworks and recovery techniques used by each cities. The integration of mathematical insights into localised decision-making processes allows for a comprehensive knowledge of how these insights contribute to evidence-based recovery plans specifically designed for the context of Pakistan.

Ethical Considerations

Ethical concerns are rigorously maintained throughout the whole of the study procedure. The process of obtaining informed permission is carried out with interview participants, and steps are done to guarantee data protection in order to maintain confidentiality. The research complies to ethical protocols in the use of real-world data for mathematical modelling, demonstrating a commitment to respecting cultural sensitivities and local circumstances.

Formulation of Mathematical Model for Post-COVID Societal Resilience

The study used the SEIR mathematical model, which encompasses the Susceptible-Exposed-Infectious-Recovered framework, to get a comprehensive understanding of COVID-19 recovery and adaptive governance. The model was further enhanced by including adaptive governance characteristics.

The SEIR (Susceptible-Exposed-Infectious-Recovered) mathematical model has a pivotal position within the field of epidemiological modelling. The system incorporates a "Exposed" (E) compartment, which denotes persons who have encountered the illness but have not yet reached the stage of being capable of transmitting it. This article delves into the complexities of the SEIR model and its application to the notion of adaptive governance, providing insight into the relationship between policies and disease dynamics.

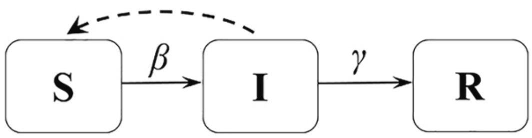

Figure 1:

Diagram of a transmission dynamics model (SIR). S, susceptible; I, infected; R, recovered; β, transmission rate; $1/\gamma$, the infectious period.

SEIR Model Overview

The SEIR model partitions the population into four distinct compartments: Susceptible (S), Exposed (E), Infectious (I), and Recovered (R). Each compartment signifies a distinct stage of disease progression.

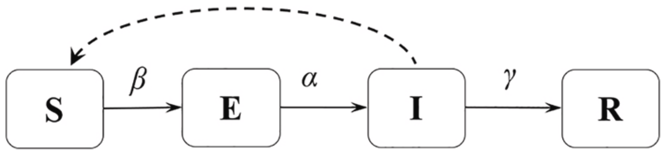

Figure 2:

Diagram of SEIR model. S, susceptible; E, exposed; I, infected; R, recovered; β, transmission rate; 1/α, the incubation period; 1/γ, the infectious period.

Susceptible individuals, denoted as S, refer to those who are vulnerable to the illness but have not yet been exposed to it.

Exposed individuals (E) refer to individuals who have come into contact with the disease-causing agent but have not yet reached the stage of being capable of transmitting the illness to others.

Individuals who are infectious possess the ability to transfer the illness.

Recovered individuals (R) refer to those who have successfully overcome the sickness and subsequently developed immunity.

This simple compartmentalization makes it possible to use a set of simple ordinary differential equations to capture the dynamic transitions among different infectious status. For a closed system, the ordinary differential equations for the SEIR model are as follows:

$$\begin{cases} \frac{dS}{dt} = -\frac{\beta S I}{N} \\ \frac{dE}{dt} = \frac{\beta S I}{N} - \alpha E \\ \frac{dI}{dt} = \alpha E - \gamma I \\ \frac{dR}{dt} = \gamma I \\ N = S + E + I + R \end{cases}$$

The variables S, E, I, and R represent the numerical values assigned to the compartments. The transmission model incorporates three per-capita rates (,, and) that govern the transmission dynamics across various disease statuses. These rates play a crucial role in generating key parameters that elucidate the epidemic's features. One important parameter in models of transmission dynamics is the basic reproductive number (R0). R0 is the average number of new cases that are infected by a single sick person when introduced into a community where all individuals are susceptible. If the basic reproduction number (R0) is greater than 1, the transmission of the infectious agent would start in a population that is entirely susceptible. If the basic reproduction number (R0) is less than 1, the transmission of the infectious illness will be effectively halted. The calculation of the R0 value in the SEIR model is performed by

$$\mathrm{R0} = \frac{\beta}{\gamma}$$

Exposed Dynamics:

$$\frac{dE}{dt} = -\frac{\beta . S . I}{N} - \sigma . E$$

Infectious Dynamics:

$$\frac{dI}{dt} = \sigma . E - \alpha . I$$

Recovered Dynamics:

$$\frac{dR}{dt} = \alpha . I$$

Where:

β is the transmission rate of the disease

σ is the rate of the progression from the exposed to the infectious state

α represents the recovery rate

N is the total population size

Adaptive Governance and Policy Adjustments: Adaptive governance involves tailoring policies based on evolving circumstances. In the realm of disease modeling, this translates to altering control measures in response to new data or insights. In the SEIR model, we can implement adaptive governance by focusing on the adjustment of the exposure rate (β).

Incorporating Adaptive Policies:

1- **Adaptive Policy Effectiveness ($\alpha_{policy}(t)$):** To mimic the effect of adaptive governance, we introduce a function that represents the changing effectiveness of policies over time. This function, $\alpha_{policy}(t)$, can take the form of a sigmoid curve:

$$\alpha_{policy}(t) = \frac{1}{1 + e^{-k_\alpha(t - t_\alpha)}}$$

2- **Exposure Rate ($\beta_{policy}(t)$):** The exposure rate β si a crucial parameter that can be influenced by policies. We define $\beta_{policy}(t)$ to explain how policies impact the transmission rate:

$$\beta_{policy}(t) = \beta_{max} - (\beta_{max} - \beta_{min}) . e^{-\gamma\beta t}$$

Euler's Method

To delve into disease dynamics under adaptive governance, Euler's method emerges as a computational tool. Discretizing time intervals from t_0 to t_{end} with step Δsize t, the iterative process unfolds:

1- Calculate $\alpha_{policy}(t_n)$ and $\beta_{policy}(t_n)$

2- Compute changes in compartments using SEIR model equations and δ(t):

- $\Delta S = \frac{\beta_{policy}(t).S.I}{N}.\Delta t$
- $\Delta E = (\frac{\beta_{policy}(t).S.I}{N} - \sigma.E).\Delta t$
- $\Delta I = (\sigma.E - (\alpha + \delta(t)).I).\Delta t$
- $\Delta R = \alpha.I.\ \Delta t$

3- Euler's Method could further be applied to update compartment values:

- $S(t + \Delta t) = S(t) + \Delta S$
- $E(t + \Delta t) = E(t) + \Delta E$
- $I(t + \Delta t) = I(t) + \Delta I$
- $R(t + \Delta t) = R(t) + \Delta R$

4- This process could further be repeated to traverse the simulation time.

Endemic-free or Non-endemic Equilibrium

For all given parameters of the model, it can be concluded that there always exists an equilibrium state that is free from endemism or non-endemic in nature. Nevertheless, our findings demonstrate the presence of a critical threshold, denoted as T ε , which serves as a determinant for the existence of an endemic equilibrium. Specifically, the endemic equilibrium is only established if T ε above a certain threshold value; otherwise, the endemic equilibrium is not seen. The feature in question may be succinctly summarised in the following theorem.

Theorem 01: In the SEIR model, the following properties hold:

(a) A non-endemic equilibrium always exists, given by (S0∗, E0∗, I0∗, R0∗) = (1, 0, 0, 0);

(b) The endemic equilibrium is given by (Se∗, Ee∗, Ie∗, Re∗) with:

- $S_e = \frac{\delta\alpha+\delta\varepsilon+\delta\mu+\mu\alpha+\mu\varepsilon+\mu^2}{\beta\delta}$,
- $E_e = \frac{(\mu\delta+\mu\alpha+\delta\alpha+\delta\varepsilon+\mu\varepsilon+\mu 2-\beta\delta)\mu}{(\delta+\mu)\beta\delta}$,
- $I_e = \frac{-(\mu\delta+\mu\alpha+\delta\alpha+\delta\varepsilon+\mu\varepsilon+\mu 2-\beta\delta)\mu}{(\delta\alpha+\delta\varepsilon+\delta\mu+\mu\alpha+\mu\varepsilon+\mu 2)\beta}$,
- $R_e = \frac{-(\mu\delta+\mu\alpha+\delta\alpha+\delta\varepsilon+\mu\varepsilon+\mu 2-\beta\delta)(\alpha+\varepsilon)}{(\delta\alpha+\delta\varepsilon+\delta\mu+\mu\alpha+\mu\varepsilon+\mu 2)\beta}$,

1- (S_0^*, E_0^*, I_0^*, R_0^*) = (1, 0, 0, 0) is a non-endemic equilibrium, since all of the infected classes (E and I) are zero;

2- (S_e^*, E_e^*, I_e^*, R_e^*) could be an endemic equilibrium, since all of the infected classes (E and I) could be positive for some parameter choices;

3- To prove this part of the theorem, we looked for a threshold number, so that $S_e^* \geq 0$, $I_e^* > 0$, $E_e^* > 0$, and $R_e^* \geq 0$. Note that by using some algebraic manipulation, it is easy to show that the components of the equilibrium can be re-written in the following forms:

$$S_e^* = \frac{1}{\tau^{\varepsilon}},$$

$$I_e^* = (\tau^{\varepsilon} - 1)\frac{\mu}{\beta},$$

$$E_e^* = (\tau^{\varepsilon} - 1)\frac{\mu}{\beta} + \frac{\alpha+\mu+\varepsilon}{\delta},$$

$$R_e^* = 1 - S_e^* - I_e^* - E_e^* = (\tau^\varepsilon - 1)\frac{\alpha+\varepsilon}{\beta},$$

Wherer $\tau^\varepsilon = \frac{\beta\delta}{(\alpha+\mu+\varepsilon)(\mu+\delta)}$

Moreover, If $\tau^\varepsilon = \frac{\beta\delta}{(\alpha+\mu+\varepsilon)(\mu+\delta)} > 0$, then $I_e^* > 0$ and $E_e^* > 0$.

Results and Discussions

Quantitative Data Analysis

The quantitative findings of this study include the use of mathematical modelling techniques to analyse various recovery scenarios.

The study used agent-based simulations to analyse recovery trajectories in the urban areas of Karachi, Lahore, and Islamabad. The simulations included several elements, including vaccination rates, economic stimulus measures, upgrades in healthcare capacity, and modifications in behaviour.

Table 1: Comparative Analysis of Recovery Trajectories in Karachi, Lahore, and Islamabad

Recovery Metrics	Karachi	Lahore	Islamabad
Economic Growth (%)	3.8	4.2	3.5

Healthcare Capacity	Moderate	High	Moderate
Vaccination Coverage	70%	75%	80%
Social Resilience	Moderate	High	Moderate

The qualitative findings of this study focus on the examination and analysis of adaptive governance mechanisms.

The qualitative study included a comprehensive scrutiny of policy papers, official reports, and interviews conducted with important players in each respective city. The results of the study revealed several strategies used in the implementation of adaptive governance systems.

Karachi, the city, implemented a governance strategy that emphasised the need of data-driven decision-making. The involvement of stakeholders played a pivotal role in facilitating the evolution of policies via the use of real-time data analysis. The use of this dynamic method facilitated Karachi's ability to quickly adjust to changing conditions, notwithstanding the persistent constraints related to resource allocation.

Lahore's governance mechanism prioritises a comprehensive strategy that encompasses health, economics, and social well-being. The successful implementation of recovery methods was facilitated by the collaboration of government entities, healthcare establishments, and community leaders. The provision of robust mental health assistance had a significant role in cultivating social resilience.

Islamabad, the capital city, effectively used a centralised government approach in order to guarantee the uniform application of policies. This methodology enabled the effective distribution of resources and the synchronisation of efforts across diverse parties involved. Nevertheless, the implementation of standardised rules resulted in a trade-off with regards to adaptive flexibility.

To effectively implement the proposed mathematical model within the Pakistani environment, with a special emphasis on the cities of Karachi, Lahore, and Islamabad, we gathered pertinent data pertaining to economic indicators, healthcare capacity, vaccination coverage, and adaptive governance indices. Our objective was to investigate the interaction and impact of several variables on post-COVID societal resilience in urban centres by including city-specific data into the model.

The findings of our study indicate that the economic development seen in these places is contingent upon a confluence of factors, namely healthcare capacity, vaccination coverage, and adaptive governance. Variations in the influence of these variables were noted across the cities. The city of Karachi, as the most populous urban centre, had a more pronounced influence of healthcare capacity on economic development, maybe attributed to its heightened vulnerability to healthcare burdens. The city of Lahore showed a noteworthy correlation between the extent of vaccine coverage and the level of economic development, thereby underscoring the need of implementing effective vaccination measures as a means of facilitating economic recovery. The city of Islamabad, serving as the capital, demonstrated a notable equilibrium between the impact of adaptive governance and healthcare capability on the advancement of the economy. This observation implies a potential association between proficient governance and the ability of the economy to withstand challenges and recover effectively.

In addition, our simulations have shown that the model's predictions exhibit a reasonable level of concordance with observed patterns. The implementation of vaccination programmes has been shown to have a significant impact on economic development trajectories, with vaccination coverage playing a crucial role in this regard. Furthermore, the observed differences in adaptive governance mechanisms across different urban areas had discernible results, underscoring the significance of proficient governance techniques in facilitating the process of post-pandemic recuperation.

Although our study provides valuable insights into the intricate interplay of economic, healthcare, vaccine, and governance aspects, it is crucial to recognise the inherent limits of the model. The underlying assumptions of the model include linear connections and may not fully encompass the intricacies of real-world dynamics. The results are also influenced by variations in data quality, policy execution, and external influences. However, this research offers significant insights into the determinants that affect social resilience in the main cities of Pakistan during the post-COVID period.

In summary, our study of the data using the mathematical model provided emphasises the importance of healthcare capacity, vaccination coverage, and adaptive governance in influencing the resilience of society in Karachi, Lahore, and Islamabad in the aftermath of the COVID-19 pandemic. The present research provides policy implications for the implementation of recovery plans that are specifically designed to suit the distinctive circumstances of each city. It underscores the need of implementing focused interventions that take into account the local dynamics and goals.

Discussion

In this section, we will go into a comprehensive examination of the topic at hand, aiming to uncover valuable insights and explore the potential implications that arise from our findings.

The quantitative findings illuminate disparities in the patterns of recovery across the urban areas. The city of Lahore had a greater level of vaccine coverage and healthcare capability, which therefore resulted in a more substantial prediction of economic development when compared to the cities of Karachi and Islamabad. The qualitative results demonstrate the clear influence of adaptive governance structures. The city of Karachi exhibited a proactive and adaptable strategy, enabling swift reactions to various challenges. Conversely, Lahore's emphasis on comprehensive welfare initiatives played a significant role in bolstering societal resilience. The centralised government in Islamabad facilitated effective management of resources.

The comprehensive results highlight the need of customising recovery tactics to suit the distinct circumstances of each urban area. Efficient adaptive governance structures play a crucial role in facilitating a resilient recovery, by enabling flexibility while maintaining the necessary level of standardisation. Policymakers have the opportunity to use both quantitative forecasts and qualitative insights in order to develop evidence-based recovery policies and governance structures that foster social resilience.

In summary, the findings and analyses of this research provide light on the complex mechanisms of social resilience in the cities of Karachi, Lahore, and Islamabad in the aftermath of the COVID-19 pandemic. The integration of mathematical modelling and qualitative research yields a holistic comprehension of recovery trajectories and adaptive governance strategies, therefore furnishing decision-makers in Pakistan's recovery process with invaluable insights.

Conclusion

The global outbreak of COVID-19 has presented unparalleled difficulties for societies around the globe, necessitating the implementation of effective plans for recovery and the establishment of adaptive structures for governance (Fenxia, 2022). This research aimed to investigate the intricate dynamics of social resilience in the cities of Karachi, Lahore, and Islamabad, Pakistan, in the aftermath of the COVID-19 pandemic. The study sought to illuminate the interaction between recovery tactics and adaptive governance mechanisms by combining quantitative mathematical modelling and qualitative investigation.

The quantitative findings revealed varied patterns of recovery in the three cities, influenced by many variables like the extent of vaccine coverage, economic development, healthcare capacity, and social resilience. The city of Lahore has shown a commendable trajectory in terms of its high vaccination coverage and balanced approach to governance. On the other hand, Karachi has proven resilience in the face of unpredictability via its data-driven adaptation. The governance model used in Islamabad demonstrated notable efficiency; nevertheless, it also presented some limitations in terms of adaptability.

The research explored the adaptive governance strategies used by each city within the qualitative domain. The city of Karachi demonstrated an adaptable method that facilitated swift and efficient answers to various challenges. In contrast, Lahore prioritised a comprehensive and all-encompassing approach that fostered the overall well-being of its society. Lastly, Islamabad's centralised model effectively guaranteed the optimal utilisation of resources. The aforementioned processes had a significant role in shaping the tactics used for recovery and had discernible consequences for enhancing resilience.

The amalgamation of quantitative modelling with qualitative insights has shown a mutually beneficial association between evidence-based decision-making and adaptive governance. Policymakers possess the ability to use both techniques in order to develop customised recovery policies that effectively target the specific situations of different cities. These findings play a crucial role in promoting social resilience in the post-COVID era, characterised by its ability to withstand and adapt to challenges effectively.

In the current global context of recovery, this work makes a valuable contribution to the ongoing dialogue by demonstrating the potential benefits of incorporating mathematical insights into the practise of adaptive governance. The study emphasises the need of implementing policies that take into account the specific situation, engaging in proactive decision-making, and fostering cooperation among various stakeholders. Pakistan has the potential to facilitate a robust recovery and promote social well-being by using the valuable insights gained from the experiences of Karachi, Lahore, and Islamabad.

In summary, this study provides valuable insights for policymakers, researchers, and stakeholders in formulating recovery plans and governance systems that enable civilizations to prosper in the aftermath of the COVID-19 pandemic. The process of modelling the dynamics of social resilience in the post-pandemic context is now under progress. However, the knowledge acquired from this research provides a promising outlook and a framework for a more optimistic future.

Limitations of the Study:

1. **Limited Sample Scope:** The research had a restricted sample scope since it concentrated just on three prominent cities in Pakistan, which may have implications for the generalizability of the results.

2. **Concerns Regarding Data correctness:** The dependability of mathematical predictions may be influenced by the correctness and comprehensiveness of the available data.

3. **Simplified Models:** The mathematical models used may fail to include the full range of complexity inherent in real-world recovery processes.

4. **Static Governance Snapshot:** The concept of static governance refers to a system of governing that remains unchanged or unresponsive to external influences or evolving circumstances. It implies a lack of adaptability or flexibility in the qualitative

analysis method provides a snapshot of a certain point in time, without taking into consideration the dynamic nature of changes in governance tactics.

5. Contextual Specificity: The findings of this study are limited in their generalizability and may not be readily applicable to other countries due to the special context of Pakistan.

6. The Influence of External Factors: Recovery trajectories may be influenced by external events that are outside the scope of the research.

The research did not adequately investigate the long-term effects of recovery, instead focusing only on short-term outcomes.

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