systems

MDPI

Article

Assessing the Impact of Risk Factors on Vaccination Uptake Policy Decisions Using a Bayesian Network (BN) Approach

Hafiz Waqar Abbas [1], Zaman Sajid [2] and Uyen Dao [3,*]

[1] School of Public Policy and Administration, Xi'an Jiaotong University, Xianning West Road, Xi'an 710049, China; hafizwaqarabbas@stu.xjtu.edu.cn
[2] Mary Kay O'Connor Process Safety Center, Artie McFerrin Department of Chemical Engineering, Texas A&M University, College Station, TX 77843-3122, USA; zaman.sajid@tamu.edu
[3] Division of Population Health and Applied Health Sciences, Faculty of Medicine, Memorial University, St. John's, NL A1B 1Z5, Canada
* Correspondence: utdao@mun.ca

Abstract: This study evaluates the propagation impact of three risk categories (hazard and exposure, socio-economic vulnerability, and lack of coping capacity) and their associated factors on vaccination uptake policy decisions in Pakistan. This study proposed Bayesian influence diagrams using expert elicitation and data-driven approaches. The Bayesian network (BN) approach uses the best policy algorithm to determine the expected utility of decisions. The study found that the government's firm vaccine uptake decisions had a positive effect in Pakistan. The findings on hazard and exposure-related factors show that people living in rural areas were more susceptible to COVID-19 than people living in urban areas. Among socio-economic vulnerability factors, household characteristics were affected due to household economic situations, fear of using health facilities due to the spread of COVID-19, lack of public transportation services, food insecurity, a temporary halt in education, and weak governance, which affected the vaccination uptake decision. The factors linked with coping capacity show that the government's financial assistance and development of digital platforms raised digital health literacy and increased vaccine uptake decision utility. The proposed methodology and results of this study can be used to develop contingency planning for any future potential pandemic situations.

Keywords: COVID-19 risk; vaccination decision; hazard and exposure; socio-economic vulnerability; lack of coping capacity

Citation: Abbas, H.W.; Sajid, Z.; Dao, U. Assessing the Impact of Risk Factors on Vaccination Uptake Policy Decisions Using a Bayesian Network (BN) Approach. *Systems* **2024**, *12*, 167. https://doi.org/10.3390/systems12050167

Academic Editor: Ed Pohl

Received: 26 March 2024
Revised: 28 April 2024
Accepted: 1 May 2024
Published: 8 May 2024

1. Introduction

By the end of December 2019, the severe acute respiratory syndrome Coronavirus 2 or COVID-19 had continued to evolve in various waves, posing a long-term threat to global public health and the economy [1]. Policymakers adopted strict control measures to contain the deadly COVID-19 pandemic, including the administration of mass vaccines to achieve herd immunity objectives [2]. It is well known that herd immunity is one of the main factors limiting the spread of disease from person to person. The experts suggested that the COVID-19 pandemic could be ended by attaining a threshold of 60–90% herd immunity [3,4]. However, the success of COVID-19 vaccination programs and herd immunity will depend on the people getting vaccinated, and, from experience, vaccine uptake can be a more significant challenge than vaccine development [5,6]. Therefore, the mandatory uptake of COVID-19 vaccines is considered the most effective and sustainable strategy for controlling the pandemic in the long term [7,8].

Since December 2020, several COVID-19 vaccines have been available worldwide with proven efficacy and safety [9,10]. Data from early clinical studies have demonstrated that vaccines against COVID-19 effectively reduce the spread of this infection and COVID-19 cases, hospitalizations, unfavorable outcomes, and deaths among individuals vaccinated against this virus [11–13]. Universal vaccination of the population against COVID-19 disease is essential for the safe achievement of herd immunity and the containment of the COVID-19 pandemic [14–16]. However, in many countries, the rollout of COVID-19 vaccines has been hampered by many factors, including issues with affordability, supply, storage, resources, logistics, public confusion, and the promotion of misinformation [17]. A key aspect of COVID-19 vaccine development and successful provision is vaccine hesitancy [18,19]. Before the COVID-19 pandemic, the World Health Organization had named vaccine hesitancy as one of the top ten threats to global health, and this issue grew even more acute in light of the COVID-19 outbreak [20].

Vaccine hesitancy is a wicked problem due to its many causes, difficulty of description, and lack of a clear solution [21,22]. It is imperative to note that vaccine hesitancy has time- and context-specific characteristics that are influenced by socioeconomic motivations, environmental circumstances, and reasons that determine individual intentions. According to the WHO model of vaccine hesitation, three factors contribute to vaccine hesitancy: (1) confidence (e.g., the degree of trust that one can place in a vaccine or a provider); (2) complacency (a condition in which an individual does not see the value and need of vaccines); and (3) convenience (i.e., barriers to accessing vaccination services) [23]. Further, research has shown that no single set of factors responsible for vaccine hesitancy influences vaccine uptake [24].

1.1. Global Overview of Vaccine Hesitancy Factors That Influence COVID-19 Vaccine Uptake

Many factors need to be considered in order to understand vaccine hesitancy in detail, and these vary depending on the context, time, location, and type of vaccine [25]. An earlier systematic review of COVID-19 vaccination intentions within the first year of the pandemic comprised 30 articles and was presented in [26]. Based on their study findings, sociodemographic differences, perceptions of risk and susceptibility to COVID-19, and vaccine attributes all influence vaccination uptake intention. In addition, a negative relationship was found between the community's acceptance of COVID-19 vaccines and vaccine safety, efficacy, mistrust of health authorities, information in social media about the vaccines, and low confidence in the health system.

AlShurman and colleagues [27] analyzed 48 peer-reviewed articles published between November 2019 and December 2020. They presented their study's findings under seven themes: demographics, social factors, vaccination beliefs and attitudes, vaccine-related perceptions, perceptions related to health, perceived barriers, and vaccine recommendations. Additionally, factors such as age, gender, education level, race/ethnicity, vaccine safety and effectiveness, influenza vaccination history, and self-protection from COVID-19 were most strongly associated with intent to take the COVID-19 vaccine. During the same year, Al-Jayyousi, G.F. et al. [28] performed a second review that included 50 studies and collected global data on attitudes toward COVID-19 vaccination. Their review provides insight into how public attitudes toward COVID-19 vaccination differ worldwide. Their research also demonstrated that these attitudes were influenced by various factors at multiple levels of the socio-ecological model. At the end of June 2021, Lazarus, J.V. et al. [29] examined vaccine uptake in 23 countries and the reasons for vaccine hesitancy within the context of uneven access, administration, and acceptance of the COVID-19 vaccine worldwide.

Further, a rapid review of the evidence concerning the determinants and strategies to increase COVID-19 vaccine acceptance in low- and middle-income countries is presented in [30]. This study found that vaccine acceptance was significantly higher among males, individuals with higher education, those with higher socio-economic status, those who were single, and those who were employed in the healthcare industry. More pieces of evidence showed that misinformation concerning COVID-19 vaccines, as well as public concerns about the safety of vaccines, had contributed to lower acceptance rates. Their study found that direct engagement with communities through influencers, such as community leaders and health experts, is a crucial approach to increasing vaccine acceptance rates. Trust in the government was also identified as a significant enabler of improvement in vaccination acceptance. Another evidence-based review was also helpful [31], which examined acceptance and hesitancy towards the COVID-19 vaccine across 15 survey samples covering 10 LMICs in Asia, Africa, South America, Russia, and the United States. They found that LMICs in their sample were significantly more likely to wish to receive the COVID-19 vaccine than Americans and Russians. In their study, the personal protective benefit of vaccination was the most frequently cited reason for vaccine acceptance. However, side effects were the most commonly cited reason for vaccine hesitancy.

Roy, D.N. et al. [32] presented a global review of COVID-19 vaccine hesitancy in 2022. Their study examined and described 11 potential common factors. According to studies conducted in Asian countries, safety, efficacy, side effects, effectiveness, and conspiracy beliefs were the most frequently encountered concerns. Among Europeans, side effects, trust, and social influence were the most influential factors influencing the decision to receive COVID-19 vaccines. In contrast, in the United States, information sufficiency, political role, and vaccination mandates played the most significant role. By the end of 2022, the study of Fajar, J.K. et al. [33] had provided valuable information about the global prevalence of COVID-19 vaccination hesitancy and the potential factors that contribute to it. Their analysis identified that vaccination hesitancy was associated with the following factors: being a woman, being 50 years or younger, being single, being unemployed, living with five or more individuals in the household, having an educational attainment lower than an undergraduate degree, working in a non-healthcare-related field, and believing COVID-19 vaccines to be unsafe. Living with children, maintaining physical distance norms, being tested for COVID-19, and receiving an influenza vaccination in the past few years also reduced COVID-19 vaccination hesitancy. Based on the findings of these published research articles, vaccine hesitancy factors that can influence the uptake of vaccine decisions against COVID-19 are emerging issues on a national, continental, and global scale.

1.2. Research Gaps

As of yet, most systematic reviews and meta-analyses of COVID-19 vaccination hesitancy and resistance have focused on assessing acceptance and rejection rates of the vaccine at the global and regional levels. However, few studies have attempted to summarize the common factors that influence the uptake of the COVID-19 vaccine. The most prevalent determinants affecting vaccination uptake policy decisions included vaccine efficacy, vaccine side effects, distrust in healthcare systems, religious beliefs, and trust in information sources of vaccines. Furthermore, demographic variables such as age, gender, education, and geographic location shape vaccination intentions. Factors including health disparities, socio-economic disadvantages, systemic racism, and exposure to online misinformation additionally influenced vaccine hesitancy. Studies have also highlighted additional determinants of vaccine hesitancy, such as social influences, political dynamics, vaccine mandates, and fear and anxiety. In existing research on vaccine hesitancy and uptake, there has been a predominant focus on individual-level factors, often overlooking broader risk dimensions that influence the vaccination uptake rate. Previous studies typically examined vaccine hesitancy through a narrow lens, failing to fully capture the complex interplay between various risk factors and their influence on vaccination decisions. For instance, while socioeconomic factors have been acknowledged as essential determinants of vaccine uptake, their interaction with other risk dimensions, such as hazard exposure and coping capacities, has not been thoroughly explored. Consequently, the holistic understanding of vaccine hesitancy and uptake has been limited.

This study identifies a significant gap in the literature, specifically the need for comprehensive exploration into the three risk dimensions: hazard and exposure, socioeconomic vulnerability, and lack of coping capacities, along with their associated factors. Specifically, the study highlighted a need for more publications thoroughly examining the pertinent factors contributing to these risk dimensions. These factors include population characteristics, sanitation and hygiene conditions, seasonal variations, health and education infrastructure, food security, economic conditions, household characteristics, financial assistance programs, governance structures, institutional capacity, infection diagnostic capacity, pharmaceutical availability, and non-pharmaceutical interventions. These factors are referred to as "risk factors" in the context of vaccination uptake due to their potential to influence individuals' vulnerability to the pandemic and willingness to accept vaccination. The term "risk" in this study implies the likelihood of adverse outcomes, such as increased susceptibility to COVID-19 infection or reduced vaccine acceptance rates. This risk manifests through various pathways, including socio-economic disparities, limited access to healthcare, misinformation, mistrust in healthcare systems, and structural barriers to vaccination access.

These factors' multidimensional and interconnected nature underscores their potential to significantly influence exposure to pandemic risk and vaccination uptake decisions. Depending on the specific context, these factors may influence individuals' vulnerability to the pandemic and willingness to accept vaccination. For instance, vaccine hesitancy's temporal and spatial dynamics remain poorly understood. Factors such as demographic characteristics of the population interact with seasonal variations in disease prevalence, localized outbreaks, or changes in public health messaging over time, and these can all influence vaccination decisions. Still, their effects have yet to be systematically studied.

Additionally, socio-economic factors such as household characteristics, economic situation, consumption patterns, transportation, and access to healthcare may play a prominent role in shaping vaccination uptake decisions, while governance structures and institutional capacity may impact the effectiveness of public health interventions. These factors can significantly shape vaccine hesitancy and uptake patterns within specific communities or geographic regions. Yet, their impact on vaccination behavior needs to be adequately examined.

Addressing the identified research gap is crucial for informing evidence-based vaccination strategies and improving public health outcomes. By taking a holistic approach to understanding vaccine hesitancy and uptake and considering the broader socio-economic and environmental factors, policymakers and public health authorities can develop more effective interventions tailored to the specific needs of diverse populations. Ultimately, this can lead to higher vaccination coverage rates and better control of the COVID-19 pandemic.

Thus, this study considered the multidimensional risk factors that can influence COVID-19 vaccination decisions based on the INFORM COVID-19 risk warring tool. The INFORM COVID-19 risk model was jointly developed by the Joint Research Center (JRC) and the scientific and technical lead of INFORM. They described three dimensions of risk: hazards and exposure, vulnerability, and lack of coping capacity [34]. Theoretically, the hazard and exposure dimensions of the model represent the likelihood of exposure to infectious agents under different conditions [34]. In the context of COVID-19 risk and its influence on vaccination uptake policy decisions, the hazard refers to the transmission of the virus, particularly its variants, which poses a significant threat to the public [35]. Exposure encompasses population density, social interaction patterns, and healthcare infrastructure, determining the likelihood of individuals contracting the virus [36]. Understanding the distribution of COVID-19 cases and identifying high-risk areas is crucial for targeting vaccination efforts effectively. The main origins of this concept can be traced back to various disciplines such as geography, environmental science, health sciences, administrative science, and disaster studies [37]. It draws heavily from risk assessment, management theories, and research on natural hazards and their impact on human populations. In this study, the origin of this concept belongs explicitly to epidemiology and public health research, emphasizing the importance of assessing both the spread of the virus and the vulnerability of populations to infection. Thus, it is imperative to understand the interrelationship between hazard and exposure, since there can be no risk without exposure, regardless of the severity of the hazard event.

Understanding the interrelationship between hazard and exposure is crucial, as they collectively form one of the core dimensions of risk. This understanding is essential for assessing vulnerability, identifying at-risk populations or areas, and implementing targeted interventions to mitigate potential harm [38]. By recognizing this risk dimension, policymakers can develop policies and regulations to reduce risk and enhance resilience, while emergency responders can plan and allocate resources more effectively during disasters. Moreover, this understanding informs public health strategies, such as vaccination campaigns or education initiatives, by identifying the populations most susceptible to infectious diseases or other health risks. Recognizing the interplay between hazard and exposure is essential for enhancing community safety, minimizing adverse outcomes, and building resilience to hazards and disasters.

The second theoretical component of risk is socio-economic vulnerability. It encompasses the susceptibility of communities or individuals to the adverse effects of hazards due to their social and economic circumstances [39]. It includes factors such as poverty, inadequate infrastructure, limited access to resources, and unequal distribution of wealth and power. The origins of this concept can be found in social science theories related to inequality, marginalization, and social stratification [40]. Scholars and practitioners have long recognized that vulnerability to a pandemic is not solely determined by physical exposure but is also influenced by underlying social and economic conditions [41]. COVID-19 has highlighted existing socio-economic disparities that influence vulnerability to the virus. Factors such as income inequality, access to healthcare, and employment conditions impact individuals' ability to protect themselves from infection and access vaccination services. Vulnerable populations, including low-income communities, racial and ethnic minorities, and marginalized groups, are disproportionately affected by the pandemic due to underlying social and economic inequalities. Addressing socio-economic vulnerability is essential for ensuring equitable vaccine distribution and overcoming barriers to vaccination uptake. This concept draws on theories of social determinants of health and health equity, highlighting the interconnectedness of social and economic factors with health outcomes [34].

The third theoretical component of risk is the lack of coping capacity. It extends to physical infrastructure, health systems, and institutional and management capacity [34]. It is defined as the capacity of a country to conduct activities before, during, and after infectious disease hazard event(s) [42]. If the pandemic risk is much higher than the coping capacity, this dimension is transformed into a lack of coping capacity. It encompasses a lack of material resources (e.g., emergency services, infrastructure) and intangible factors (e.g., social cohesion, institutional effectiveness). The origins of this concept can be traced to research on resilience and adaptation, as well as to theories of disaster preparedness and response [34]. Understanding the factors that enhance or diminish coping capacity is essential for designing effective risk-reduction strategies and building resilience in vulnerable communities. Theoretically, coping capacity in the context of COVID-19 refers to the ability of healthcare systems, public health agencies, and communities to respond to the challenges posed by the pandemic [43], which includes factors such as healthcare infrastructure, availability of vaccines and medical supplies, and coordination of response efforts. Countries with weak healthcare systems and ineffective pandemic preparedness plans are not equipped to manage the vaccination rollout and mitigate the impact of COVID-19 on public health [44]. This concept draws from disaster preparedness and resilience theories, emphasizing the importance of adaptive capacity in responding to complex health emergencies like COVID-19.

Consequently, the three risks mentioned above and their relevant factors influencing vaccination uptake decisions are highly interrelated; therefore, it is a challenging task to consider the propagation impact of pandemic risk factors when assessing vaccination uptake decisions.

1.3. Decision-Making in the Context of Vaccination Uptake

In decision-making, particularly in public health crises such as viral epidemics, assessing decision-makers' utility is paramount. This process hinges on a meticulous evaluation of available evidence spanning various factors. Understanding the intricate interplay between individual behavior and disease dynamics is essential in shaping effective public health strategies [45]. For instance, Tomassen F. et al. [46], in response to the foot-and-mouth disease outbreak, introduced a model aimed at mitigating direct costs and export losses across diverse scenarios. Similarly, Sok J. et al.'s [47] model of dairy heifer management delved into the complexities of vaccination decisions, recognizing the disparate estimation methodologies between animal and human epidemics. Navigating the complexities of the COVID-19 pandemic further underscores the challenges facing policymakers worldwide. Karnon, J. et al.'s [48] exploration of lockdown versus gradual response approaches highlights the multifaceted nature of pandemic decision-making.

Thus, policymakers are confronted with the daunting task of weighing the benefits of mandating vaccination against the risks of maintaining the status quo, particularly in the face of low vaccine uptake and the ensuing potential for increased infection rates. What exacerbates the dilemma is the need for further examination into how policymakers can effectively evaluate the value of their vaccination decisions and navigate the myriad risks posed by pandemics. As such, a critical gap exists in understanding how decision utility can be quantified and how policymakers can assess the propagation impact of epidemic risk categories. These risk categories—hazard and exposure, socio-economic vulnerability, and lack of coping capacity—are pivotal in shaping vaccination uptake policies. Our interest lies in delving into these nuanced aspects, aiming to shed light on how policymakers can effectively evaluate the value of their vaccination decisions amidst pandemic risks. By quantifying decision utility and examining the propagation impact of epidemic risk categories within network settings, we seek to offer insights that can inform evidence-based policymaking in the face of unprecedented public health challenges.

In this study, we conceptualize COVID-19 epidemic risk and operationalize a data-driven process combining expert elicitation to assess the relative significance of multidimensional factors influencing vaccination uptake decisions and provide informed decision support on whether vaccination enforcement will be effective in the four provinces of Pakistan. Additionally, this study identifies critical factors in a network setting while considering their propagation impact by proposing a Bayesian influence diagram. Here, the network setting means a dynamic framework illustrating the interconnectedness of factors contributing to epidemic risk within a community, including hazard and exposure, socioeconomic vulnerability, and lack of coping capacity. During the COVID-19 outbreak, these factors interact and collectively shape vaccine uptake decisions. Hazard and exposure dynamics, such as close-knit communities or densely populated areas, influence individuals' risk of disease transmission, while socioeconomic vulnerabilities exacerbate disparities in vaccine access and adherence.

Additionally, communities' lack of coping capacity impacts individuals' ability to respond effectively to health threats, further influencing vaccine uptake decisions. By recognizing these interconnected factors within the network setting, public health interventions can be tailored to address the multifaceted determinants of vaccine acceptance and coverage, leveraging social networks to disseminate accurate information, build trust, and overcome barriers to vaccination access, ultimately enhancing public health outcomes. The resulting prioritization scheme can assist policymakers in developing appropriate strategies to view network-wide epidemic risks that influence vaccine uptake decisions. Also, by understanding the characteristics of different populations and the factors that affect vaccination uptake, evidence-based multilevel interventions can be planned to enhance vaccine uptake rates in Pakistan and other countries where policymakers face similar issues.

2. Materials and Methods

2.1. Study Area

Like other countries, vaccine hesitancy and low uptake are not new phenomena in Pakistan [49]. Vaccination campaigns and programs in the past have made slow progress, which is evidence of this: BCG (Bacillus Calmette Guerin) vaccination coverage was reported at 80%, polio vaccination coverage was 60%, and measles vaccination coverage was 67% [50]. Many factors influence vaccination product promotions in Pakistan. These factors include political, religious, and commercial factors; logistical challenges; insufficiently trained healthcare professionals; parents who do not know what to do; organizational factors; socio-economics; and environmental circumstances [51]. To what extent these factors have contributed to vaccine hesitancy among the Pakistani population is unknown. A clear understanding of the factors that influence vaccine uptake remains elusive.

Furthermore, anti-vaccination groups, which denied the existence of COVID-19, contributed to slowing vaccine uptake rates in Pakistan [52]. Therefore, the government of Pakistan made a firm vaccination uptake decision across the country. The firm vaccination uptake decision across the country refers to a comprehensive and steadfast approach taken by government authorities or health agencies to ensure widespread acceptance and administration of COVID-19 vaccines among the population. This decision involves implementing innovative strategies and initiatives to maximize vaccination coverage and achieve herd immunity against the virus. Thus, the effective vaccination enforcement planning was tailored to local needs (like other non-pharmacological interventions) and paved the way for the containment of the disease due to its effectiveness. As a result, Pakistan's COVID-19 control strategy has been praised internationally, but the utility of the vaccination uptake policy decisions has not been studied. Therefore, having noticed a gap in the literature and the need for related research, we aim to determine the propagation impact of three risk categories (hazard and exposure, socio-economic vulnerability, and lack of coping capacity) on vaccination uptake policy decisions in four provinces of Pakistan within a network setting.

2.2. Evaluation Strategy

The proposed approach is theoretically based on Bayesian Influence Diagrams (BIDs), which can be used to model and assess uncertainties within a networked environment [53,54]. Although BIDs have been utilized across various areas in pandemic risk analysis, their application has been limited to exploring focused problems such as analyzing vaccine uptake by enforcing policy decisions. In this regard, leveraging BIDs to explore the complexity associated with the multidimensional nature of the COVID-19 pandemic risk on vaccination uptake decisions is imperative. The evaluation strategy of this study consists of four steps, as presented in Figure 1. It was applied to four provinces of Pakistan, namely, Punjab, Sindh, Baluchistan, and KPK, to assess the effectiveness of COVID-19 vaccination enforcement policy decisions in each region.

Step 1: Identification of risk dimensions and associated factors

In this step, three COVID-19 risk categories were derived from the INFORM COVID-19 warring tool [34]: hazard and exposure, socio-economic vulnerability, and lack of coping capacity. Each risk category was further classified into risk factors. In the INFORM COVID-19 warring model for this study, several key factors contribute to the hazard and exposure of COVID-19 risk and subsequently impact the decision-making process regarding vaccine uptake. These factors, derived from the existing literature, are interconnected through causal relationships. Firstly, population dynamics play a significant role, where the average annual growth rate of the population directly influences population density. It, in turn, affects the population distribution between rural and urban areas, with implications for average household size.

Furthermore, changes in average household size further influence the distribution of the population across rural and urban areas. Additionally, environmental factors, including access to improved sources of drinking water and sanitation facilities, contribute to seasonal variations, which directly impact both rural and urban populations. These environmental factors also contribute directly to hazards and exposure to infectious diseases, including COVID-19. Understanding these interconnected relationships is vital for comprehending the dynamics of COVID-19 risk and vaccination uptake decisions, facilitating the development of targeted strategies to mitigate risks, and enhancing vaccine uptake across different population groups.

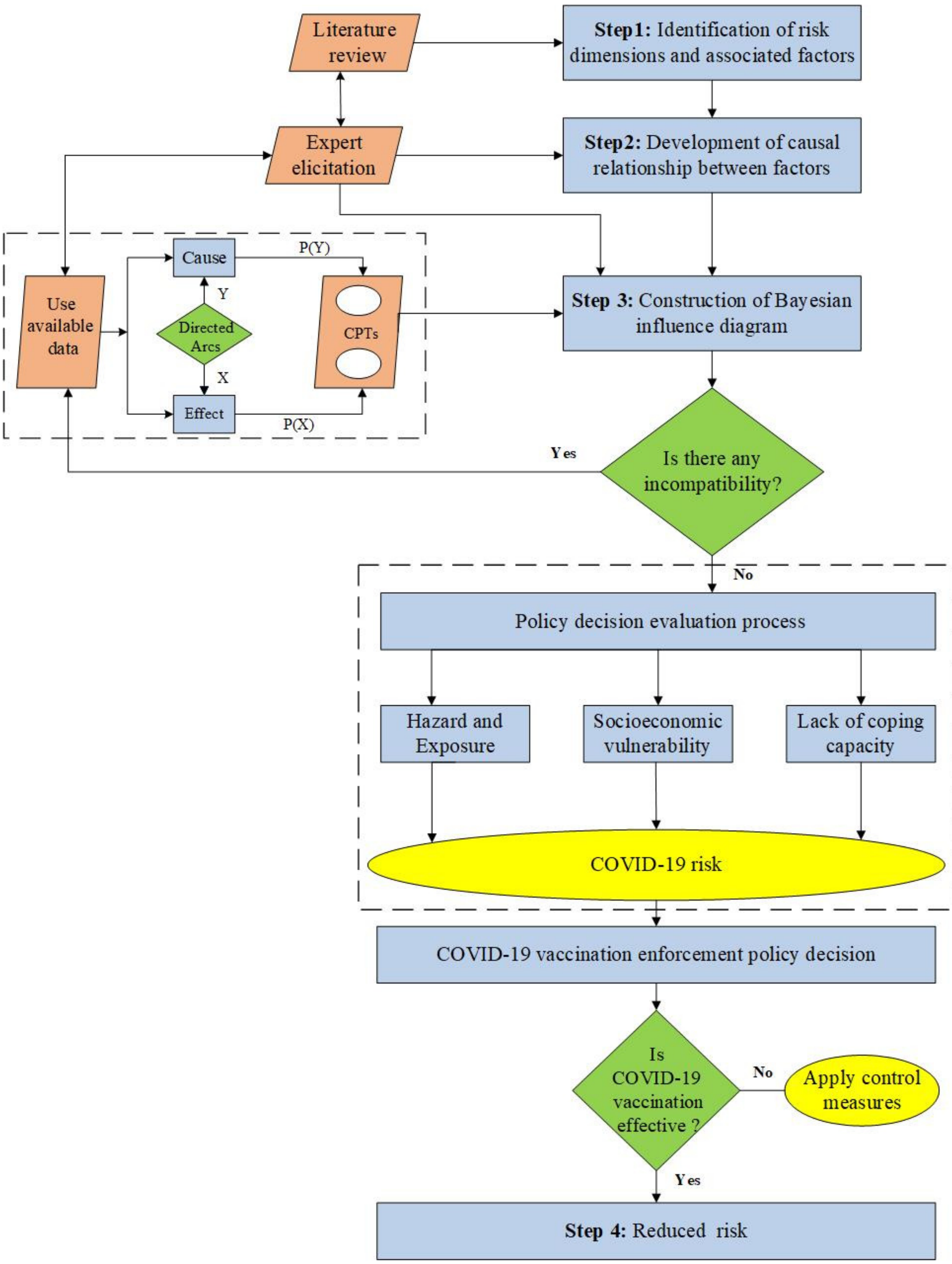


Figure 1. Research methodology diagram.

In the INFORM COVID-19 warring model for this research, several key factors contribute to socio-economic vulnerability, impacting the decision-making process regarding vaccine uptake. These factors, informed by existing literature, are interconnected through causal relationships. The closure of businesses due to COVID-19 lockdowns is a pivotal factor directly influencing household economic situations. Consequently, economic conditions directly affect household consumption, contributing to socio-economic vulnerability. This vulnerability, in turn, directly influences the decision-making process regarding vaccination uptake. A lack of use of health facilities due to fear of COVID-19 and the lack of transportation services directly impact household characteristics. These household characteristics, in turn, directly influence household consumption expenditures and indirectly contribute to socio-economic vulnerability, which subsequently affects vaccine uptake decision utility.

Moreover, food insecurity is directly linked to household characteristics and contributes to socio-economic vulnerability, influencing vaccine uptake decisions. Furthermore, temporary halts in education and weakness in the governance system and institutional capacity are identified as direct contributors to socio-economic vulnerability and indirectly influence vaccine uptake decision utility. Understanding these interconnected relationships is crucial for designing targeted interventions to address socio-economic vulnerabilities and enhance vaccine uptake in affected populations.

In this study's INFORM COVID-19 warring model, various key factors contribute to the lack of coping capacity, subsequently influencing the decision-making process regarding vaccine uptake. These factors, drawn from existing literature, are interconnected through causal relationships. Government assistance emerges as a pivotal factor linked with seven specific aspects: the development of a COVID-19 app by the government, public awareness programs (including handwashing, mask-wearing, and social distancing), COVID-19 immunization coverage, COVID-19 quarantine facilities (including isolation beds), public-funded labs for COVID-19 testing, designated tertiary hospitals for COVID-19 treatment, and financial support for vulnerable populations through programs like "Ehsaas". The government's development of a COVID-19 app directly facilitated access to computers and mobile phones with internet connectivity for the population. Which, in turn, enhanced COVID-19 data sharing and collection mechanisms, impacting the availability of quarantine facilities. In addition to directly affecting medical assistance programs and public-funded labs for COVID-19 testing, these facilities contributed to the overall lack of coping capacity, influencing vaccine uptake decision utility. Public awareness programs and financial support initiatives for vulnerable populations are directly associated with the lack of coping capacity. Indirectly, they contributed to the decision-making process regarding vaccine uptake.

Furthermore, COVID-19 data sharing and collection mechanisms, COVID-19 immunization coverage, and designated tertiary hospitals directly impacted the availability of quarantine facilities. These factors, in turn, indirectly contributed to the lack of coping capacity, which subsequently influenced the decision-making process regarding vaccine uptake. Understanding the intricate interplay between these factors is essential for devising effective strategies to bolster coping capacities and enhance vaccine uptake in communities affected by COVID-19.

Further, secondary data on each risk factor were identified from national household surveys and the National Command and Control Center of COVID-19 Pakistan [55–62]. Detailed information regarding the risk categories and each risk factor definition are presented in Table S1.

Step 2: Development of causal relationships

This step uses expert elicitation to build causal relationships among risk factors. This approach has been extensively used in the literature [63,64]. Expert elicitation is a systematic process to gather and integrate expert opinions, knowledge, and judgments on a particular topic, mainly when empirical data are limited or unavailable. In this study focused on COVID-19 vaccination uptake decisions in Pakistan, expert elicitation played a crucial role in assessing the relative significance of multidimensional factors influencing vaccination decisions. Initially, a diverse panel of experts with expertise spanning public health, epidemiology, healthcare policy, and socio-economic factors relevant to COVID-19 vaccination was carefully selected. These experts were then engaged through structured interviews or surveys designed to elicit their insights and opinions on various dimensions, including hazard and exposure, socio-economic vulnerability, and coping capacity.

During these interactions, experts were asked to provide their judgments or assessments on the relative importance or impact of different factors identified in the theoretical framework. Their responses were systematically aggregated and synthesized to identify patterns, trends, and areas of consensus or disagreement. Statistical methods or qualitative analysis techniques were employed to analyze the data and derive meaningful insights from the expert opinions. The synthesized expert opinions were then integrated into the decision-making process related to vaccination uptake policies, providing valuable input for policymakers to prioritize interventions, allocate resources, and develop strategies to enhance vaccine uptake in Pakistan. Overall, expert elicitation was useful for synthesizing expert knowledge and informing evidence-based policy-making efforts related to COVID-19 vaccination in Pakistan. Experts developed the interdependencies and causal relationships among risk factors based on their expertise in COVID-19 research. After identifying interdependency relationships among risk factors and categories, arcs (the directional links) between nodes were defined to show causality. This step developed the three BID models for each risk category.

Step 3: Construction of Bayesian influence diagram

This step conducted a cause-effect analysis of risk factors using prior probability values, and posterior probabilities were obtained using Bayes' theorem. A BID has n decision nodes of $D_1, D_2, D_3, \ldots, D_n$; x chance nodes of $C_1, C_2, C_3, \ldots, C_n$; and utility function nodes $U_1, U_2, U_3, \ldots, U_a$. Each utility function value, given by any combination of specified and random nodes, was calculated using Equation (1). In Equation (1), U_i is the ith utility function node and $\pi(U_i)$ is the parent node group of U_i, while D is the decision node group $(D_1, D_2, D_3, \ldots, D_n)$. Further, A_p indicates the group of chance nodes and $U_i[\pi(U_i)]$ shows the utility function of U_i.

$$U_i \mid D, A_p = U_i[\pi(U_i)]P\left[\pi(U_i)/D, A_p\right] \quad (1)$$

In Equation (2), A_q represents the group of chance nodes without evidence, and $P\left[\pi(U_i), D, A_p, A_q\right]$ shows the joint probability of all parameters (nodes) in an ID.

$$P\left[\pi(U_i)/D, A_p\right] = \frac{P\left[\pi(U_i), D, A_p, A_q\right]}{P(D, A_p)} = \frac{P\left[\pi(U_i), D, A_p, A_q\right]}{\sum_{\pi(U_i), A_q} P\left[\pi(U_i), D, A_p, A_q\right]} \quad (2)$$

If all types of nodes are denoted as a group Y $(Y_1, Y_2, Y_3, \ldots, Y_n)$ in which N = n + x + a, then the joint probability P $(Y_1, Y_2, Y_3, \ldots, Y_n)$ can be expressed as the products of the conditional probability of each node given its parents, as shown in Equation (5) [65], where $\pi(Y_i)$ is the group of all parents of Y_i.

$$P(Y_1, Y_2, Y_3, \ldots, Y_n) = \prod_{i=1}^{n} P(Y_i / \pi(Y_i)) \quad (3)$$

The basic parameters of a discrete BN are stated in Equation (4) [66]. In Equation (4), (l) and (m) are the state numbers of the node Y_i and its parents, respectively.

$$\theta_{ilm} = P\ (Y_i = l \mid \pi(Y_i) = m) \quad (4)$$

According to Bayes' theorem, the vector's posterior probability is explained by Equation (5) [66].

$$P(\theta|D) \propto P(\theta) \prod_{i=1}^{n} \prod_{l=1}^{n} \prod_{m=1}^{n} \theta_{ilm}^{x_{ilm}} \quad (5)$$

where θ indicates the vector of θ_{ilm} and P(θ) shows the prior probability of θ, while x_{ilm} is illustrated by the number of samples with Y_i = i and $\pi(Y_i)$ m.

Step 4: Apply the best policy algorithm

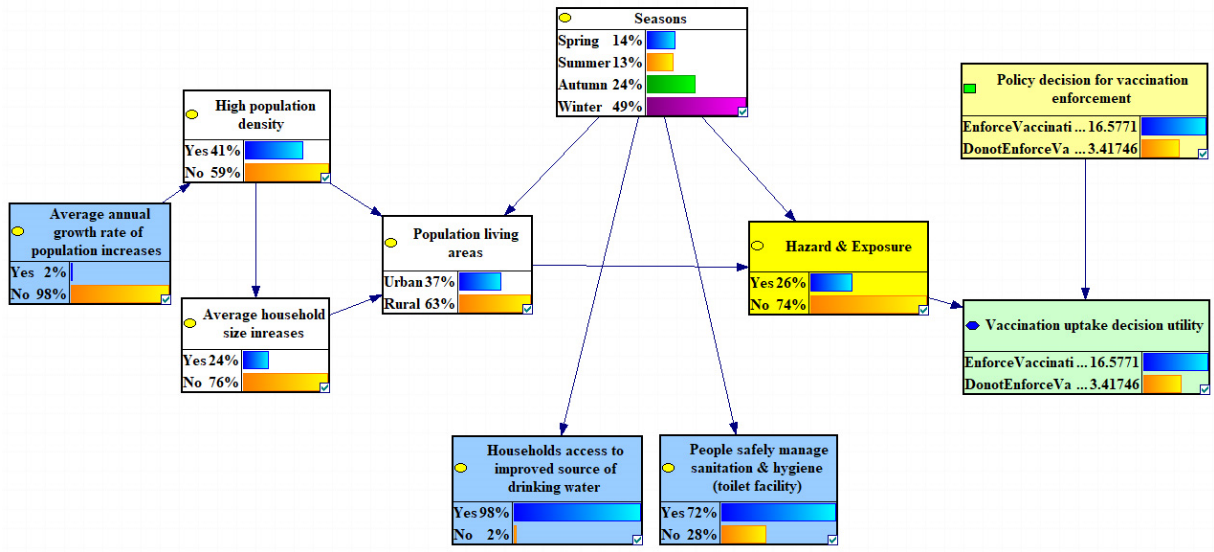
We used the best policy algorithm to calculate a strategy that yielded the highest expected utility of all possible combinations of decision nodes and observations. This policy assessment algorithm solved the BID, first by converting it into a BN and then by finding the expected utility of each option by performing the repeated process of inferring in a network setting. The algorithm resulted in a complete set of expected utilities for all possible decisions in the network. The application and reliability of such an approach have been well-studied in the literature [67,68]. GeNie software (Version-9.4.7) was used to analyze this study.

3. Results

Table S1 lists twenty-nine risk factors identified for three risk categories, and the results for each risk category in four provinces (Punjab, Sindh, KPK, Balochistan) of Pakistan are discussed in this section.

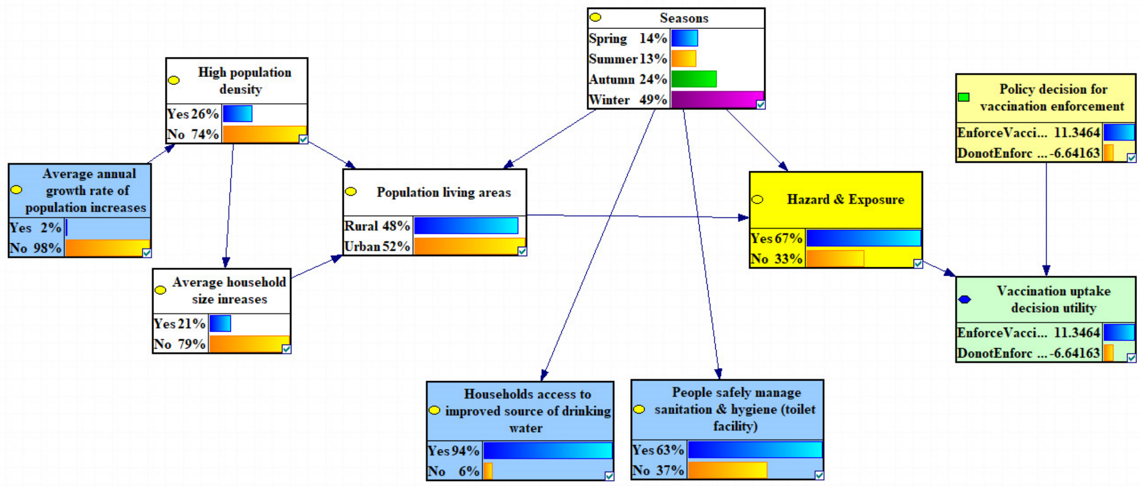
3.1. Hazard and Exposure Results

The BID model's results regarding hazard and exposure in four provinces (Punjab, Sindh, KPK, Balochistan) of Pakistan are presented in Figure 2A–D, illustrating the contextual relationships among nine risk factors. The results reveal the interconnections among these factors. Specifically, the analysis demonstrates that the average annual growth rate of the population directly impacts the population density. Furthermore, population density directly influences the average household size and the population distribution between rural and urban areas. These demographic factors, in turn, exhibit a direct relationship with hazard and exposure, exerting an indirect influence on the decision utility related to vaccination uptake. Additional findings highlight the significance of households' access to an improved source of drinking water and the effective management of sanitation and hygiene by the populace. These two factors contribute to environmental considerations. The environmental factor emerges as critical due to its impact on the population residing in rural and urban areas and its influence on hazard and exposure. The intricate web of these nine factors collectively affects the decision utility associated with vaccination uptake.

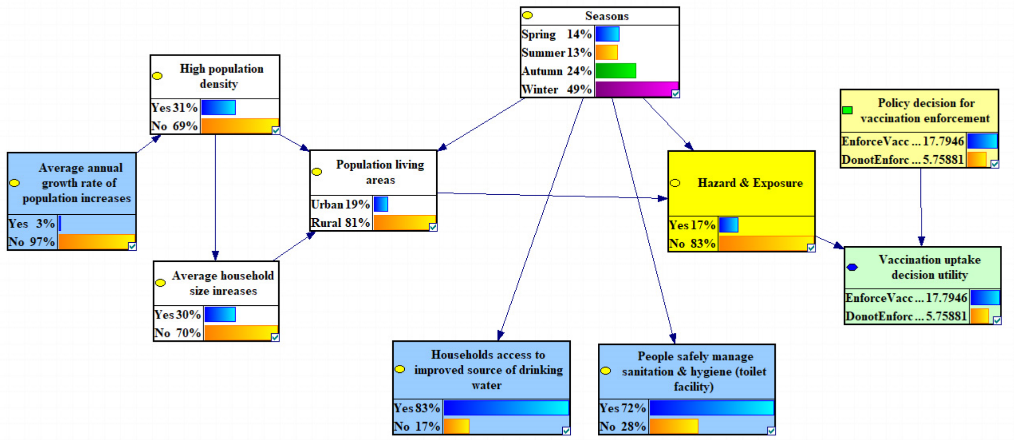


(A)

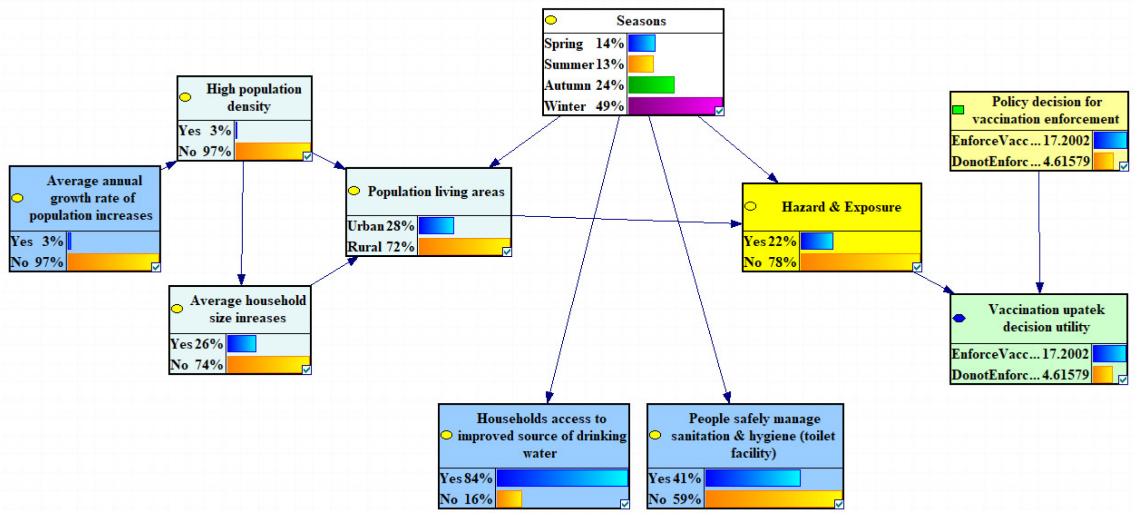
Figure 2. *Cont.*



(**B**)



(**C**)

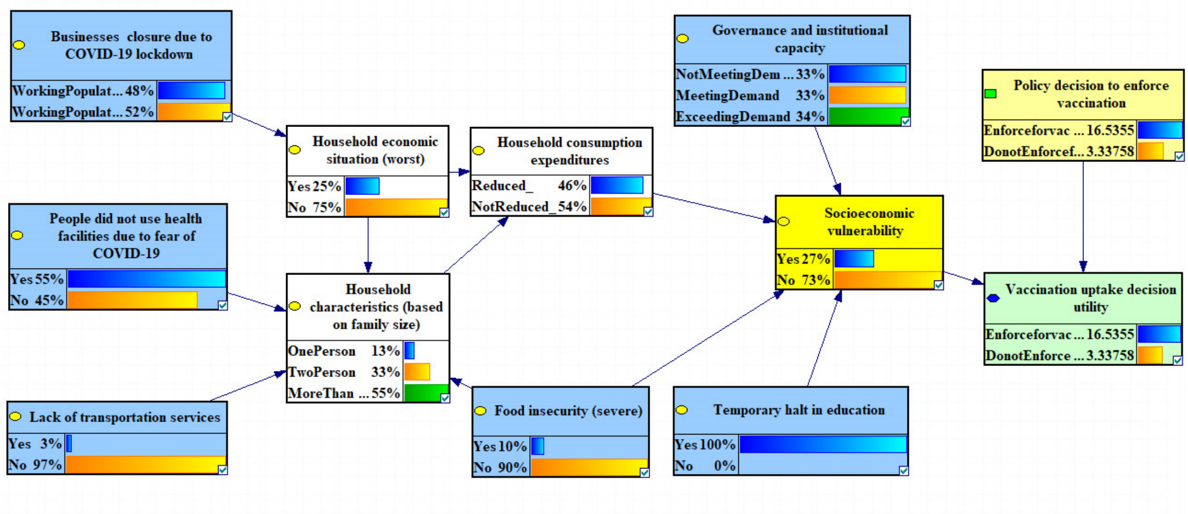


(**D**)

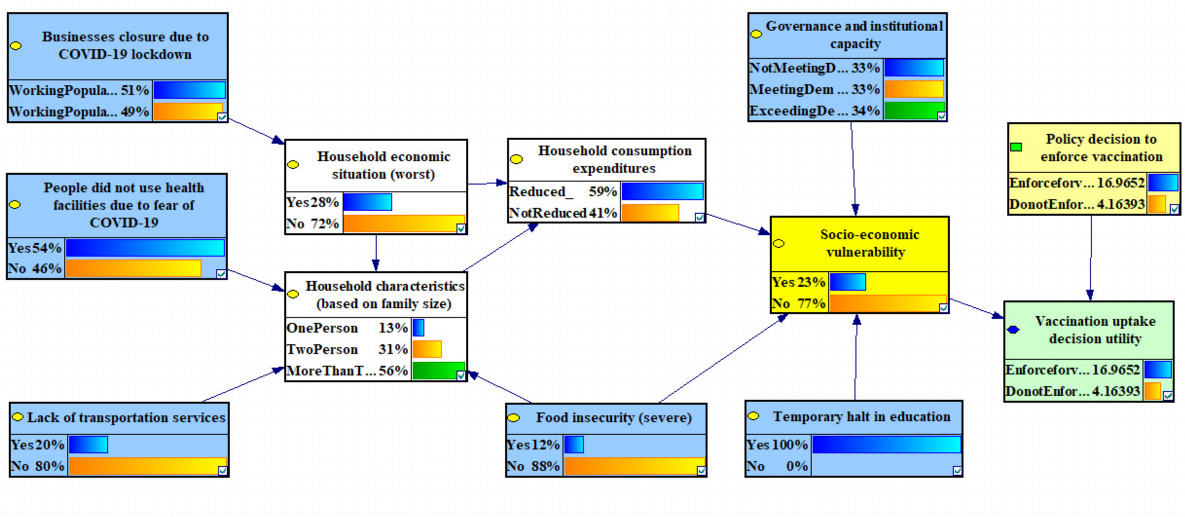
Figure 2. (**A**) Hazard and exposure BID for Punjab province, (**B**) hazard and exposure BID for Sindh province, (**C**) hazard and exposure BID for KPK province, and (**D**) hazard and exposure BID for Balochistan province. Input nodes are colored blue, output nodes are highlighted in yellow, and intermediate nodes are highlighted in white. Light green represents the utility node, and light yellow indicates the decision node. This color scheme is followed in all simulated figures of this work.

3.2. Socio-Economic Vulnerability

The BID model's outcomes regarding socio-economic vulnerability in four provinces of Pakistan (Punjab, Sindh, KPK, Balochistan) are depicted in Figure 3A–D, encompassing ten contextual risk factors. Among the identified factors, three stand out as particularly crucial: "Businesses closure due to COVID-19 lockdown", "No use of health facilities due to fear of COVID-19", and "Lack of transportation services". Moreover, the results underscore the significance of household economic situations and characteristics. Both of these factors directly influence household consumption expenditure, serving as direct contributors to socio-economic vulnerability. Consequently, they also indirectly affect the decision utility associated with vaccination uptake. Further insights from the results highlight that factors such as "Food insecurity", "Temporary halt in education", and "Governance and institutional capacity" indirectly impact vaccination uptake decision utility through their contributions to socio-economic vulnerability.

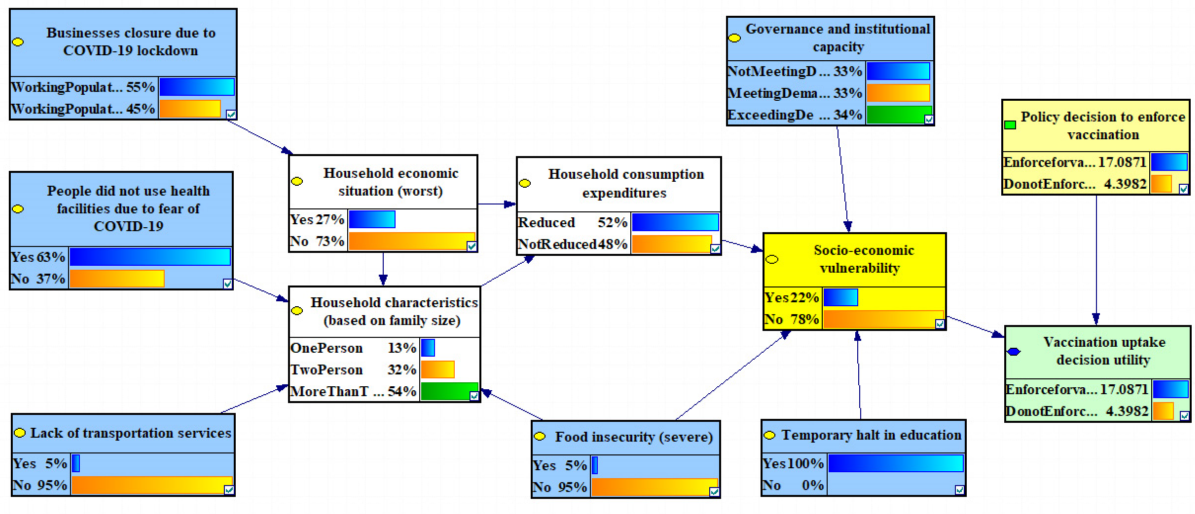


(**A**)

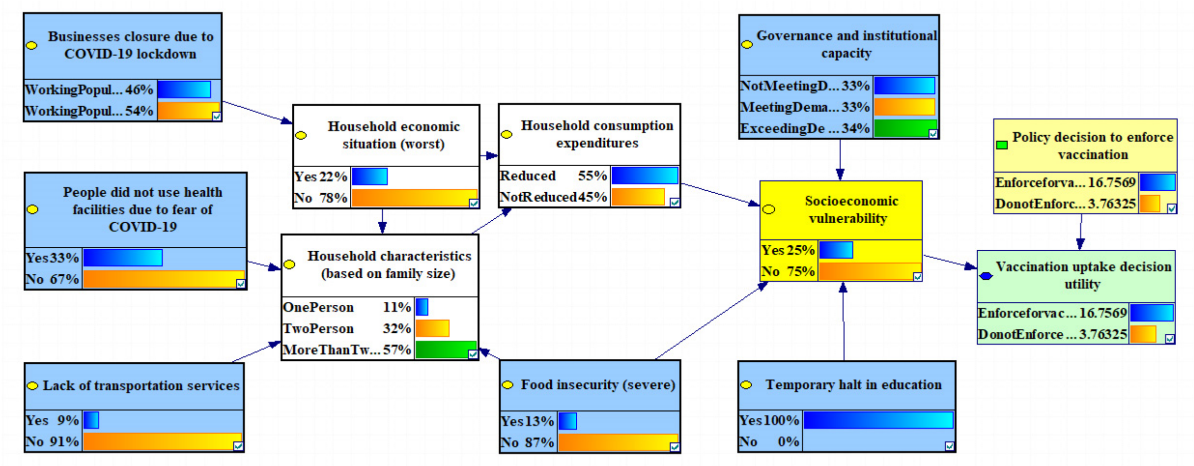


(**B**)

Figure 3. *Cont.*



(**C**)

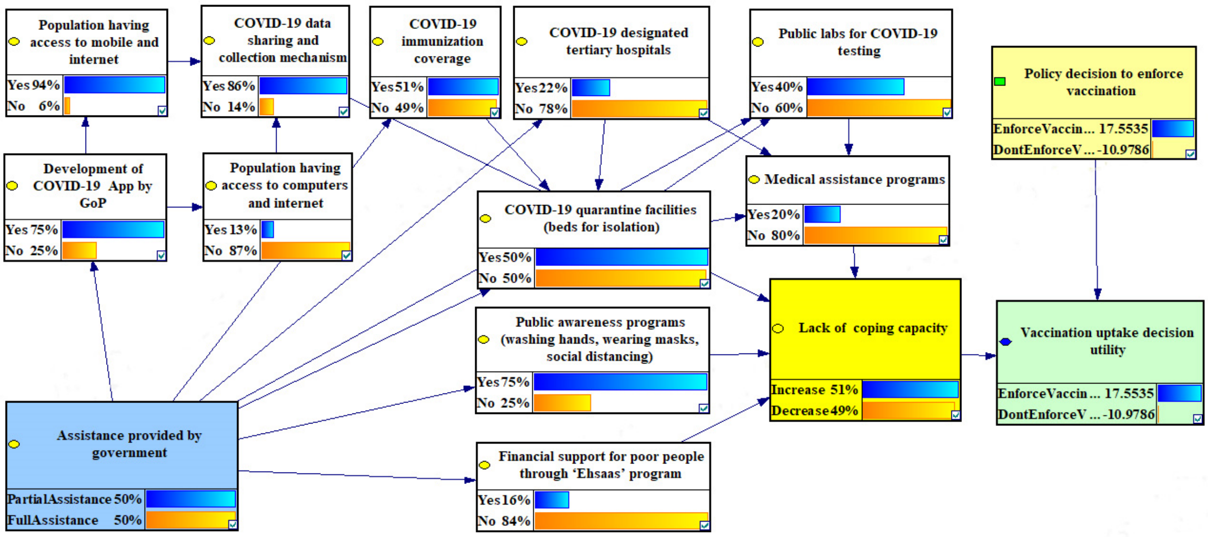


(**D**)

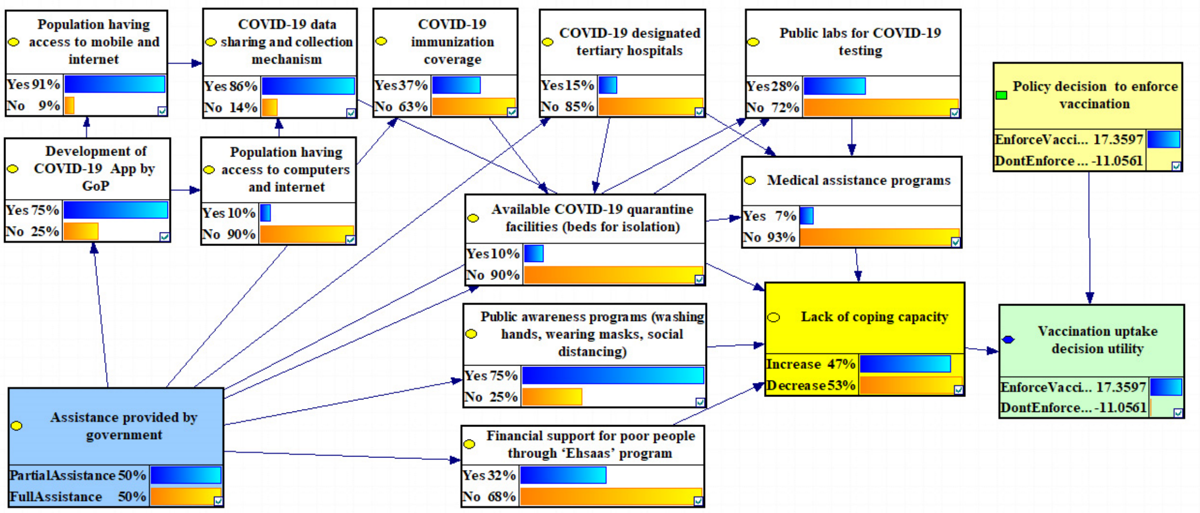
Figure 3. (**A**) Socio-economic vulnerability BID for Punjab province, (**B**) socio-economic vulnerability BID for Sindh province, (**C**) socio-economic vulnerability BID for KPK province, and (**D**) socio-economic vulnerability BID for Balochistan province. Input nodes are colored blue, output nodes are highlighted in yellow, and intermediate nodes are highlighted in white. Light green represents the utility node, and light yellow indicates the decision node. This color scheme is followed in all simulated figures of this work.

3.3. Lack of Coping Capacity

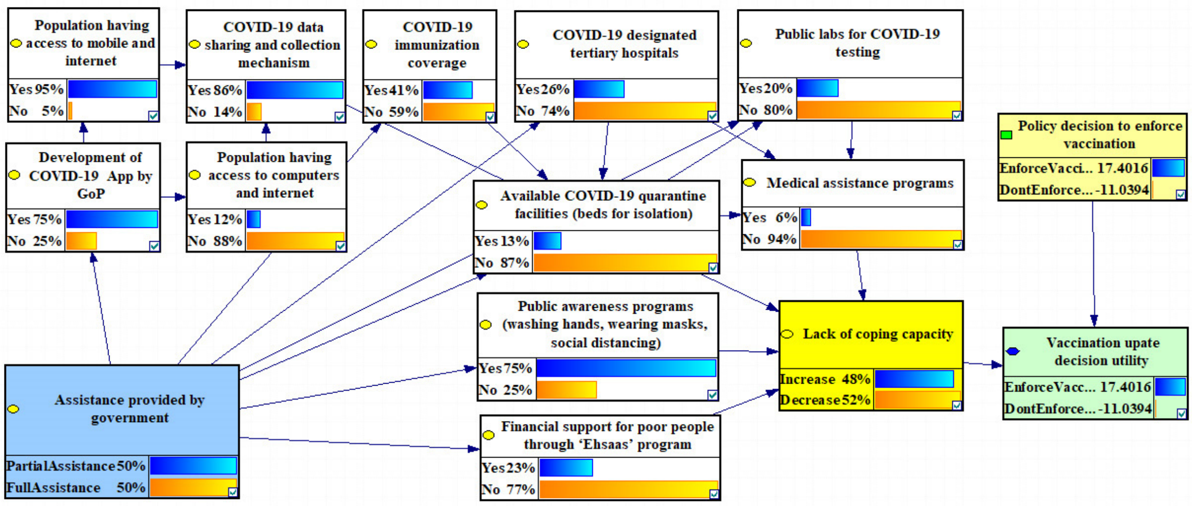
The BID model's insights into the lack of coping capacity in four provinces of Pakistan (Punjab, Sindh, KPK, and Balochistan) are visually represented in Figure 4A–D. The results illuminate the intricate causal relationships among 12 risk factors, emphasizing the pivotal role of governmental coping capacity in shaping decisions related to COVID-19 vaccination uptake. The analysis reveals that government assistance, highlighted as a parent node, indirectly affects vaccination uptake decision utility through the lens of coping capacity. The government's development of a COVID-19 app is crucial, influencing the population's access to computers, the internet, and mobile phones. These, in turn, directly affect the COVID-19 data sharing and collection mechanism, indirectly impacting vaccination uptake utility through coping capacity constraints.



(**A**)

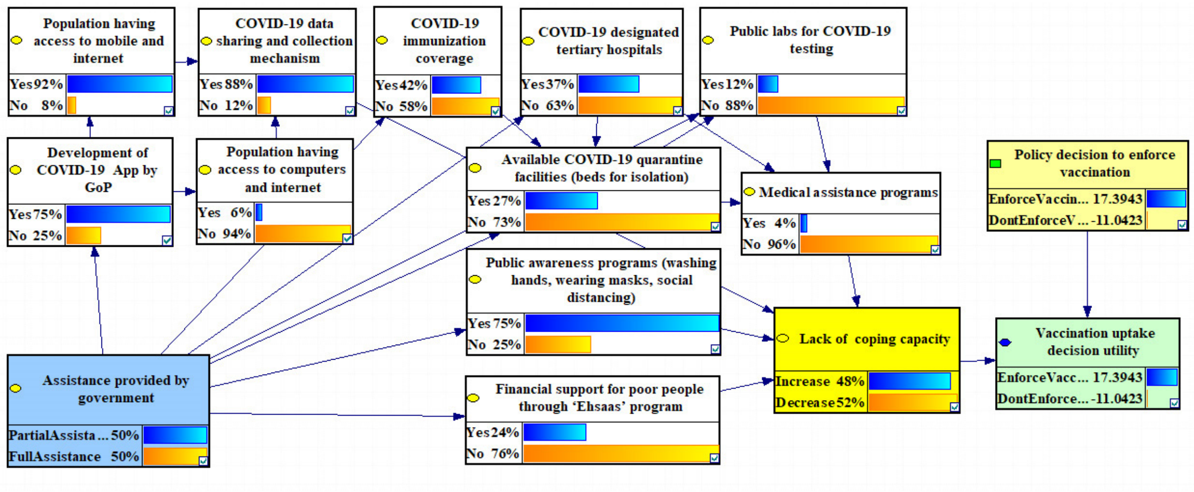


(**B**)



(**C**)

Figure 4. *Cont.*



(**D**)

Figure 4. (**A**) Lack of coping capacity BID for Punjab province, (**B**) lack of coping capacity BID for Sindh province, (**C**) lack of coping capacity BID for KPK province, and (**D**) lack of coping capacity BID for Balochistan province. Input nodes are colored blue, output nodes are highlighted in yellow, and intermediate nodes are highlighted in white. Light green represents the utility node, and light yellow indicates the decision node. This color scheme is followed in all simulated figures of this work.

Furthermore, the presence of COVID-19-designated tertiary hospitals is a critical node influencing medical assistance programs and the availability of COVID-19 quarantine facilities (beds for isolation). Simultaneously, these factors indirectly affect vaccination uptake utility through coping capacity constraints. Additional findings highlight the importance of COVID-19 immunization coverage, directly influencing the availability of quarantine facilities. Moreover, public awareness programs (emphasizing handwashing, mask-wearing, and social distancing), public-funded labs for COVID-19 testing, and financial support for the economically disadvantaged through the "Ehsaas" program all exert an indirect influence on vaccination uptake utility through the lens of coping capacity.

3.4. Total COVID-19 Risk

The BID model's insights into the total COVID-19 risk in four provinces of Pakistan (Punjab, Sindh, KPK, and Balochistan) are visually represented in Figure 5A–D. The total COVID-19 risk is the risk posed due to hazards and exposure, socio-economic vulnerability, and the lack of coping capacity. The concept of total COVID-19 risk encompasses the combined impact of hazards and exposure, socio-economic vulnerability, and the lack of coping capacity within a given region. The results illustrate the interconnectedness of these three components, providing a comprehensive view of the overall COVID-19 risk in each province.

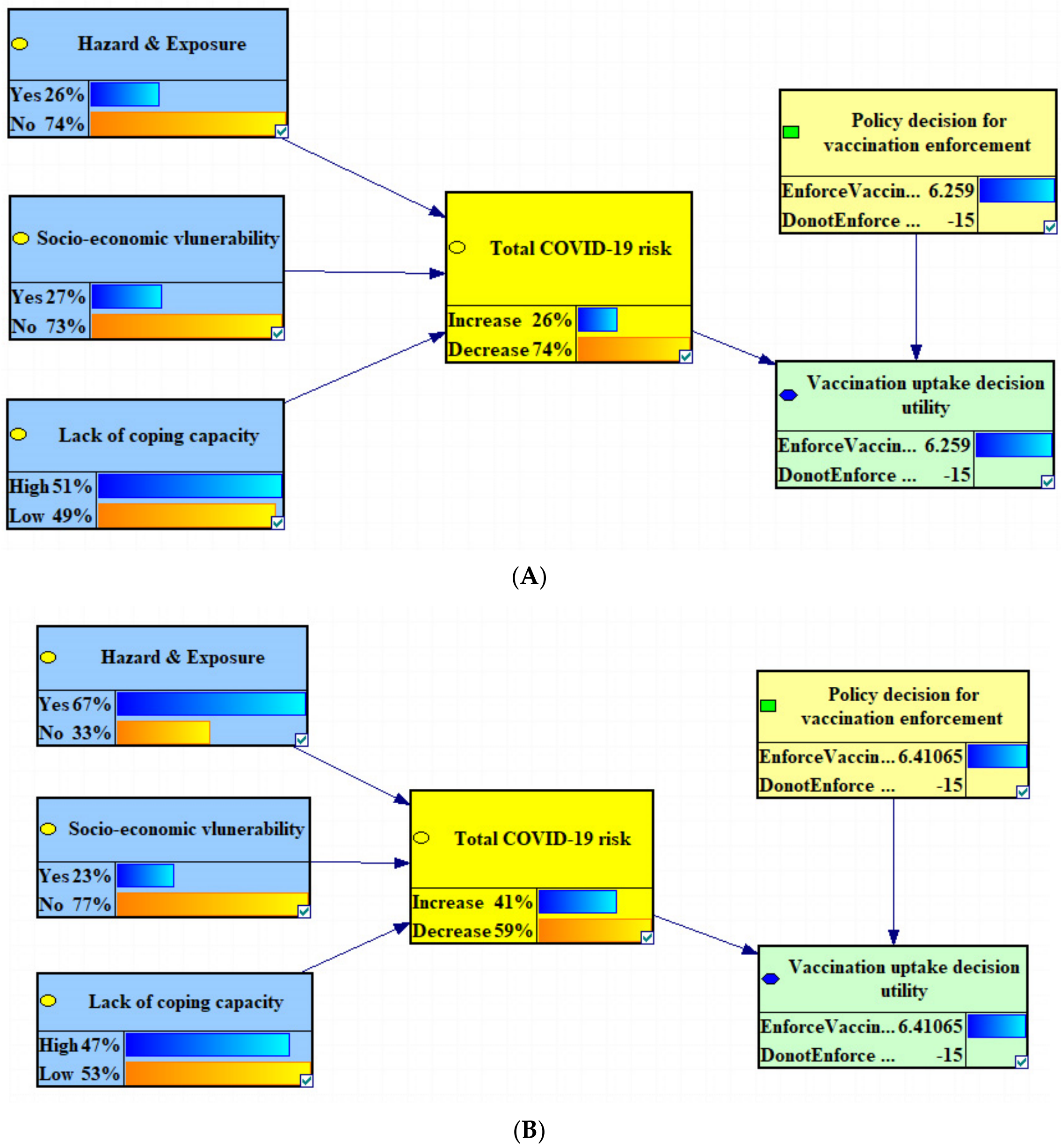
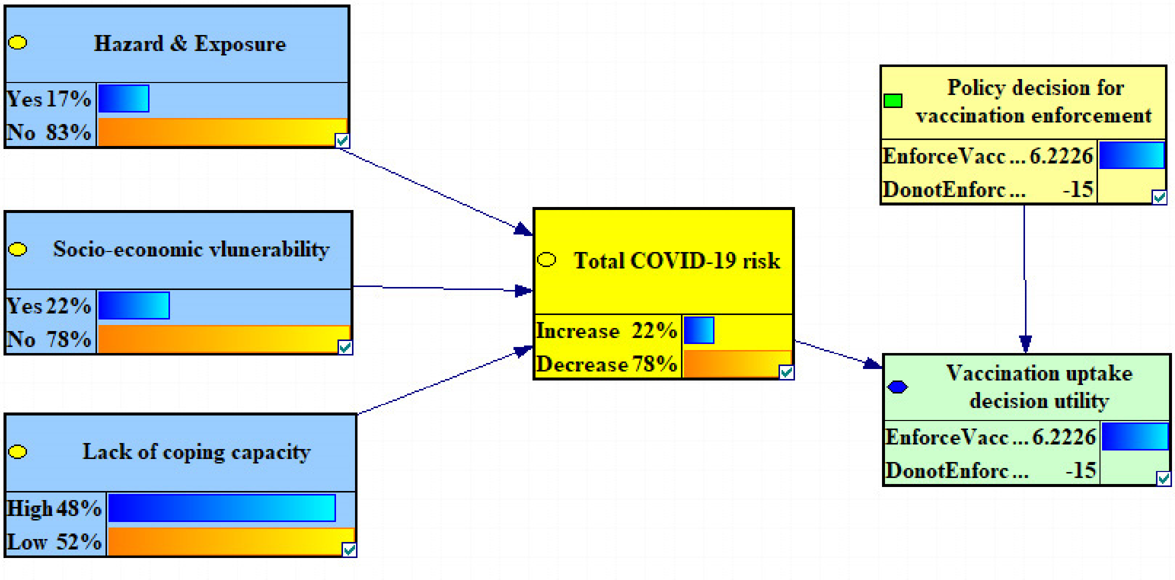
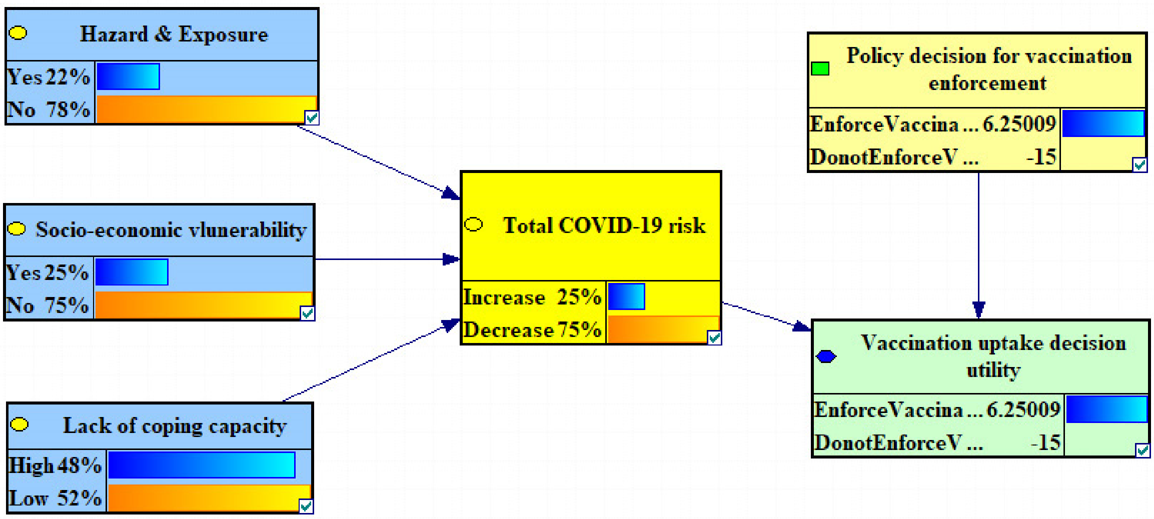


Figure 5. *Cont.*



(**C**)



(**D**)

Figure 5. (**A**) Total COVID-19 risk BID for Punjab province, (**B**) total COVID-19 risk BID for Sindh province, (**C**) total COVID-19 risk BID for KPK province, and (**D**) total COVID-19 risk BID for Balochistan province. Input nodes are colored blue, output nodes are highlighted in yellow, and intermediate nodes are highlighted in white. Light green represents the utility node, and light yellow indicates the decision node. This color scheme is followed in all simulated figures of this work.

4. Discussion

The amalgamation of hazards and exposure, socio-economic vulnerability, and the lack of coping capacity form the foundation of our examination of the multifaceted challenges posed by the pandemic. This discussion will delve into each risk component individually, exploring the nuanced dynamics, critical insights, and implications uncovered by the model. By dissecting these aspects, we aim to understand better the complex web of factors influencing the total COVID-19 risk in the specified provinces. The subsequent sections will explore hazard and exposure, socio-economic vulnerability, and lack of coping capacity, unraveling the layers of each component and deciphering their collective impact on the pandemic.

4.1. Hazard and Exposure

The BID model's intricate examination of hazard and exposure is presented in Figure 2A–D, related to four provinces of Pakistan (Punjab, Sindh, KPK, and Balochistan). It unravels a nuanced web of contextual relationships among nine risk factors. The analysis provides valuable insights into the relationship between the population's average annual growth rate, population density, and the associated hazards and exposures that individuals encounter. This understanding is particularly pertinent in the context of COVID-19 vaccine uptake in Pakistan, where densely populated areas may face heightened transmission risks. For instance, in urban centers like Karachi, Lahore, and Islamabad, high population density contributes to increased transmission rates, emphasizing the urgency of implementing proactive measures such as social distancing and mask-wearing to mitigate the risk of contracting the coronavirus. It is especially critical in regions with varying average household sizes between urban and rural areas; for example, densely populated urban areas may require stricter enforcement of vaccination uptake measures compared to sparsely populated rural regions. Moreover, the analysis elucidates the impact of seasonal dynamics on COVID-19 risks, which is crucial for informing vaccination strategies in Pakistan. The findings reveal a direct association between seasonal factors and various risk components. For instance, access to safe drinking water and adequate sanitation and hygiene practices are essential year-round but take on added significance during the four seasons, especially concerning COVID-19 hazards and exposure. Further, extreme weather conditions such as cold winters and hot summers can pose challenges to maintaining social distancing, thereby influencing exposure to COVID-19. In Pakistan, where seasonal variations are pronounced, adapting vaccination campaigns and public health messaging to account for these dynamics is essential. For example, outdoor vaccination centers and mobile vaccination units have become more effective in reaching communities during the scorching summer months. Consequently, these findings underscore the importance of developing tailored strategies to address seasonal variations in COVID-19 risk, especially concerning vaccination efforts in Pakistan.

Figure 2's results shed light on the significant influence of population size, particularly in urban and rural areas experiencing seasonal fluctuations, on decisions regarding the uptake of COVID-19 vaccination policies. This revelation highlights the intricate interplay between demographic factors, environmental conditions, and vaccination policy decisions, indicating that larger populations and extreme weather conditions may introduce additional complexities to the vaccination process. These insights showed flexible and adaptive vaccination strategies that accounted for Pakistan's diverse challenges of varying population sizes and seasonal dynamics.

The provincial-level comparison provided in Figure S1 offers valuable insights into the varying levels of COVID-19 hazard and exposure across different regions of Pakistan. Among the provinces, Khyber Pakhtunkhwa (KPK) has the lowest hazard and exposure rate at 17%. This relatively low risk could be attributed to effective early containment measures, including stringent lockdowns and robust testing and tracing efforts. Additionally, KPK's lower population density than other provinces might have contributed to reduced transmission rates. Following KPK, Baluchistan records a hazard and exposure rate of 22%, possibly due to its sparse population density and geographical isolation, which could have slowed the virus's spread. Punjab falls in the middle range, with a hazard and exposure rate of 26%, reflecting its large population size, dense urban areas, and significant economic activities. Finally, Sindh exhibits the highest hazard and exposure rate at 67%, likely due to its densely populated urban centers like Karachi and potential challenges in enforcing strict preventive measures. These provincial differences underscore the importance of tailored interventions to address each region's specific risk factors and vulnerabilities, guiding policymakers in implementing targeted measures such as vaccination campaigns and public health initiatives to combat COVID-19 effectively.

The results depicted in Figure 2A–D shed light on the utility of vaccination enforcement decisions across different provinces of Pakistan, providing valuable insights into the effectiveness of such measures in mitigating COVID-19 risks. Notably, the highest utility of vaccination enforcement decisions was observed in KPK, with a utility value of 17.79. This finding correlates with KPK's relatively lower exposure risk of 17%, which can be attributed, at least in part, to its dispersed population and less urbanized landscape. Similarly, Balochistan demonstrated the second-highest utility value for vaccination enforcement decisions, standing at 17.20. Balochistan also exhibited a relatively lower exposure risk of 22%, reflecting similar characteristics of a dispersed population and less urbanized environment contributing to reduced COVID-19 transmission rates.

In contrast, Punjab recorded a utility value of 16.57, indicating slightly lower effectiveness of vaccination enforcement decisions than KPK and Balochistan. Punjab's higher hazard and exposure rate of 26% can be attributed to its denser population and more urbanized landscape, which may have presented more significant challenges in containing the spread of COVID-19. Lastly, Sindh registered the lowest utility value for vaccination enforcement decisions at 11.34, reflecting its higher hazard and exposure rate of 67%. Like Punjab, Sindh's dense population and urbanized environment contributed to increased COVID-19 risk, underscoring the importance of targeted interventions to address these challenges effectively. These findings highlight the nuanced relationship between vaccination enforcement decisions, COVID-19 exposure risks, and provincial demographics, guiding policymakers in implementing tailored strategies to combat the pandemic.

By recognizing factors and their relationships with hazard and exposure and vaccination uptake decisions, policymakers and healthcare authorities can better target resources and interventions to maximize vaccine uptake and protect vulnerable populations effectively. Tailored vaccination campaigns considering seasonal variations in transmission dynamics and demographic differences between urban and rural areas can help to ensure equitable access to vaccines and enhance overall vaccine acceptance and uptake rates in Pakistan.

4.2. Socio-Economic Vulnerability

The results stemming from the assessment of socio-economic vulnerability across four provinces of Pakistan (Punjab, Sindh, KPK, Balochistan), as presented in Figure 3A–D, offer a profound understanding of the intricacies surrounding ten contextual risk factors. These findings illuminate how various elements intersect to shape the socio-economic landscape amidst the challenges posed by the COVID-19 pandemic. The impact of business closures due to lockdown measures directly reverberates through households in Pakistan, significantly affecting income levels and forcing people to rely on their savings to meet daily expenditures. This economic strain profoundly impacts household characteristics, particularly family size, which becomes vulnerable to four critical risk factors: household economic situation, fear of using health facilities due to COVID-19, lack of public transportation services, and food insecurity. For example, in urban areas such as Karachi and Lahore, where many businesses were forced to close during lockdowns, families reliant on daily wage labor faced immediate financial hardships, leading to increased reliance on savings and limited access to essential resources. This economic instability disproportionately affected larger families, who may have struggled to afford necessities such as food and healthcare, further exacerbating their vulnerability to COVID-19.

In Figure 3, it is shown that the household economic situation influences household consumption expenditure via two routes (direct link and indirect link). These two routes differ in terms of the directness of the relationship between household economic situation and consumption expenditure. In the direct route, the influence of economic status on consumption expenditure is immediate and observable, with changes in income or financial resources directly impacting household spending decisions. In contrast, the indirect route involves a more complex interplay of household characteristics that mediate the relationship between economic status and consumption behavior. While economic status remains a central determinant of consumption expenditure, its effects are moderated or mediated by household characteristics based on family sizes, resulting in more nuanced and context-specific consumption patterns.

Additionally, the fear of contracting COVID-19 in crowded health facilities has deterred many individuals from seeking medical care, particularly in densely populated urban centers where healthcare facilities may be overwhelmed. The fear of contracting COVID-19 when seeking medical care may disproportionately affect socio-economically vulnerable populations who already face barriers to healthcare access. For example, individuals with lower incomes or limited access to transportation may be more reluctant to seek medical attention due to concerns about potential exposure to the virus. This fear can exacerbate existing health disparities and contribute to delayed diagnosis and treatment of medical conditions among socio-economically vulnerable groups. Therefore, the reluctance to use health facilities due to COVID-19 fear reflects a socioeconomic vulnerability that impacts individuals' access to essential healthcare services. This fear, coupled with limited access to public transportation services, presents significant barriers to accessing vaccination sites, particularly for marginalized communities living in remote or underserved areas.

Furthermore, food insecurity poses a substantial challenge to vaccine uptake, especially among families with limited financial resources. In rural areas of Pakistan, where agriculture is a primary source of livelihood, disruptions to supply chains and market closures have resulted in food shortages and increased prices, making it difficult for families to afford nutritious meals. As a result, prioritizing vaccine uptake may become secondary to meeting immediate food needs for many households.

The revelation that families with more than two members face the highest risk, while those with only one member bear the least risk, underscores the differential vulnerabilities within the population. Such disparities necessitate targeted interventions to address the distinct needs of various household types. For instance, in densely populated urban areas like Faisalabad, Karachi, and Lahore, where households often consist of multiple family members living in close quarters, the risk of COVID-19 transmission is heightened due to the challenges of maintaining social distancing. Conversely, in rural areas where households are typically more prominent, with extended family members residing together, the risk of transmission may be further compounded by limited access to healthcare facilities and resources. The observed reduction in food and non-food expenditures due to food insecurity further underscores the potential deterioration in living standards, urging the government to strategize vaccination efforts for extended families. For example, in rural villages where agricultural labor is the primary source of income, disruptions to supply chains and market closures have led to decreased income and increased food insecurity among families with larger household sizes. Implementing targeted vaccination drives in these communities and initiatives to address food insecurity cannot help to alleviate socio-economic vulnerability on a broader scale.

Considering the diverse household structures in Pakistan, where urban households typically consist of fewer than six members and rural families often surpass six members, the impact of socio-economic factors is nuanced [69]. For instance, in urban slums where overcrowding is prevalent, the risk of COVID-19 transmission is higher due to limited access to healthcare facilities and sanitation services. In contrast, in rural areas where access to healthcare is limited and transportation infrastructure needs to be improved, reaching remote communities with vaccination campaigns poses logistical challenges. The results in Figure 3A–D illuminate that the reluctance to use health facilities and the lack of transportation infrastructure contribute to socio-economic risks and influence decisions related to COVID-19 vaccination uptake. For example, in remote villages where healthcare facilities are scarce and public transportation is unreliable, individuals may hesitate to seek vaccination due to concerns about accessing medical care in case of adverse reactions. In such scenarios, implementing a targeted door-to-door vaccination drive emerges as a viable strategy to navigate the challenges posed by a high degree of coronavirus risk and limited public transportation facilities.

Furthermore, the analysis exposes the ripple effects of a temporary halt in education, governance, and institutional capacity on socio-economic vulnerability, subsequently influencing decisions related to vaccination uptake. For instance, school closures and disruptions to government services may exacerbate existing socio-economic disparities, making it difficult for marginalized communities to access essential resources and information about vaccination programs. The multifaceted nature of these challenges highlights the need for comprehensive and adaptive policy measures to address the evolving socio-economic landscape and ensure equitable access to COVID-19 vaccines across diverse communities in Pakistan.

In a provincial comparison (as detailed in Figure S1), the socio-economic vulnerability was lowest in KPK (22%), followed by Sindh (23%) and Baluchistan (25%), while Punjab bore the highest socio-economic vulnerability (27%). Our analysis indicates minor differences in socio-economic vulnerabilities. By tailoring interventions to each province's specific socioeconomic contexts and needs, decision-makers can effectively maximize the impact of their efforts on health outcomes.

The findings presented in Figure 3A–D provide valuable insights into the effectiveness of vaccination enforcement decisions across different provinces of Pakistan in increasing COVID-19 vaccination uptake. Notably, KPK stands out with the highest utility value for vaccination enforcement decisions, recorded at 17.08. This indicates a positive impact on vaccination rates in the province, suggesting that targeted enforcement measures have been particularly effective in promoting vaccine uptake in KPK. Conversely, in Punjab, where socio-economic vulnerability is relatively high compared to other provinces, the utility of vaccination enforcement measures is lowest at 16.53. Which suggests that Punjab faces challenges in boosting vaccination rates despite efforts to enforce vaccination, possibly due to socio-economic factors influencing vaccine acceptance. However, both Sindh and Baluchistan closely follow, with utility values of 16.96 and 16.75, respectively, indicating similarly positive impacts of vaccination enforcement decisions on vaccination uptake in these provinces. The findings proved that positive utility values across all provinces signify the potential efficacy of vaccination enforcement decision-making in increasing vaccination rates and ultimately reducing COVID-19 transmission.

These insights underscore the critical role of tailored strategies in addressing socio-economic vulnerabilities and optimizing vaccination efforts across diverse regions of Pakistan. For instance, KPK and Baluchistan are more remote than the rest of the provinces; one potential way to improve health services is through mobile vaccination facilities. Such movable units can remove transportation barriers to accessing medical care and ensure the availability of better and quicker healthcare services. In Sindh, rural areas, where access to healthcare is limited, and literacy rates are lower than in urban centers like Karachi, community-based vaccination drives and outreach programs may be essential to reach marginalized populations and improve vaccine uptake. Similarly, in Punjab, where socio-economic vulnerability is highest, targeted interventions such as mobile vaccination clinics and door-to-door outreach campaigns may be necessary to overcome barriers to vaccination access and ensure equitable distribution of vaccines. By understanding the socio-economic dynamics of each province and implementing context-specific interventions, policymakers can enhance vaccination coverage and mitigate the impact of COVID-19 across Pakistan.

4.3. Lack of Coping Capacity

The intricacies of coping capacity in the face of the COVID-19 pandemic are unveiled through the lens of 12 risk factors in Figure 4A–D. This model intricately captures the causality relationships that underscore the pivotal role of the government's coping ability in navigating decisions related to COVID-19 vaccination uptake. The results underscore critical facets of effective coping strategies, shedding light on various dimensions that can significantly impact the success of vaccination enforcement decisions.

One noteworthy revelation is the instrumental role of financial assistance provided by the government, mainly through programs like "Ehsaas" designed to support the economically disadvantaged. For example, families in rural areas of Punjab, where poverty rates are higher compared to urban centers, have relied on financial aid from the "Ehsaas" program to meet their daily expenses during the pandemic. This financial support has enabled individuals to prioritize healthcare expenses, including vaccination costs, thereby increasing vaccine uptake among low-income communities.

Public awareness programs also emerge as powerful tools in alleviating the burden on medical facilities, emphasizing the importance of preventive measures such as hand-washing, mask-wearing, and social distancing. For instance, in urban centers like Karachi and Islamabad, where population density is high and healthcare infrastructure is strained, public awareness campaigns have played a crucial role in promoting adherence to COVID-19 guidelines and reducing transmission rates. The success of these campaigns is evident in the increased willingness of individuals to get vaccinated, as they recognize the importance of vaccination in controlling the spread of the virus and protecting themselves and their communities.

However, the study showcases the positive impact of the development of the COVID-19 app by the government of Pakistan in disseminating crucial information and fostering public awareness. In the case of the COVID-19 pandemic, the development of a COVID-19 app led to increased demand for internet access among the population in Pakistan. Individuals who previously had not prioritized internet connectivity saw the value in accessing the app for information, updates, and health-related services. This increased demand incentivized households to invest in internet-enabled devices such as computers or mobile phones. Moreover, government policies and regulations were implemented to support the widespread adoption of the COVID-19 app and increased access to internet-enabled devices. However, it is vital to recognize the digital divide, with a significant portion of the population needing access to computers and the internet posing challenges to accurate data collection through these digital channels. In rural Sindh and Baluchistan regions, where internet penetration is low, alternative strategies such as community health workers and mobile vaccination clinics may be more effective in reaching underserved populations and improving vaccine uptake rates. Given these disparities, the government must adopt a multi-pronged approach to vaccine registration and dissemination, including traditional communication channels like radio broadcasts and community outreach programs. By leveraging existing infrastructure and engaging with local communities, policymakers can address barriers to vaccine access and promote equitable distribution across diverse regions of Pakistan.

The results show that the government's efforts to immunize the masses help minimize the burden on quarantine facilities. For example, in Sindh, where quarantine facilities were stretched to their limits due to rising COVID-19 cases, successful vaccination campaigns led to a decline in hospital admissions and reduced strain on medical resources. This result is vital information since vaccination is the only permanent solution to defeating the coronavirus and minimizing the burden on quarantine facilities. Additionally, better-managed quarantine facilities can help ensure robustness in medical assistance programs and COVID-19 testing facilities, ultimately contributing to more effective pandemic control measures across Pakistan.

Further analysis reveals that inadequate governance of coronavirus quarantine facilities can significantly undermine the government's coping capacity to enforce COVID-19 vaccination measures. For instance, in regions where quarantine facilities are poorly managed, individuals may be reluctant to seek medical assistance, fearing exposure to the virus. This reluctance can exacerbate the spread of COVID-19 and hinder vaccination efforts. The study highlights the pivotal role of the medical assistance program in bolstering the government's coping ability, as it serves as a crucial link in the chain of COVID-19 response measures. However, Pakistan's healthcare infrastructure, including designated tertiary hospitals, testing labs, and quarantine facilities, needs to be improved to meet the demands of the population. With only a limited number of testing labs and hospitals available for a population of 220 million, the government's capacity to enforce vaccination decisions is significantly constrained [70]. This limitation hampers the diagnosis and treatment of COVID-19 cases and undermines public confidence in the effectiveness of vaccination efforts. As a result, addressing shortcomings in medical assistance programs is imperative to enhancing the government's coping capacity and facilitating successful COVID-19 vaccination uptake across Pakistan.

The study emphasizes the pivotal role of mass vaccination campaigns in relieving pressure on quarantine facilities, positioning vaccination as a critical strategy to mitigate the impact of the coronavirus pandemic. However, it also sheds light on the complex factors influencing the government's coping capacity, with governance deficiencies in quarantine facilities emerging as a potential obstacle. A central finding underscores the critical importance of the medical assistance program in bolstering the government's ability to respond effectively to the pandemic. This program is intricately linked to various risk factors, including the availability of coronavirus-designated tertiary hospitals, COVID-19 testing capabilities, and the management of quarantine facilities. Despite the considerable healthcare infrastructure in Pakistan, this study reveals a need for more of a focus on medical assistance programs, which limits the government's capacity to implement vaccination policies efficiently.

Thus, Figure S1 presents a comprehensive provincial comparison of coping capacity across Sindh, KPK, Baluchistan, and Punjab, revealing intriguing insights into Pakistan's regional landscape of vaccination uptake. Surprisingly, Punjab emerges with the highest degree of lack of coping capacity, standing at 51%, followed by Sindh (47%), KPK (48%), and Baluchistan (48%). Decision-makers can optimize vaccination efforts and foster equitable access to vaccines nationwide by customizing interventions to tackle the lack of coping capacity and harnessing local resources and partnerships to build resilience.

The findings presented in Figure 4A–D offer significant insights into the impact of vaccination enforcement decisions across various provinces in Pakistan, highlighting their effectiveness in mitigating COVID-19 risks. Notably, Punjab stands out with the highest utility value of 17.55 for vaccination enforcement decisions, indicating strong effectiveness in boosting vaccination rates and reducing transmission. Following closely, KPK demonstrates the second-highest utility value at 17.40, suggesting effective enforcement measures in promoting vaccine uptake. However, Sindh and Balochistan show lower utility values of 14.35 and 14.39, respectively, indicating a somewhat lesser effectiveness of vaccination enforcement decisions in these provinces. These disparities underscore the need for tailored strategies and targeted interventions to address specific challenges and enhance vaccine uptake across different regions of Pakistan. These nuanced provincial differences emphasize the necessity of customized strategies to address each region's particular challenges and strengths. By adopting a targeted approach, policymakers can further optimize vaccination efforts, ensuring a more equitable and impactful response to the ongoing COVID-19 pandemic in Pakistan.

4.4. Total COVID-19 Risk

In an extensive analysis spanning four provinces of Pakistan (Punjab, Sindh, KPK, Balochistan), the comprehensive findings presented in Figure 5A–D unveil the outcomes of total COVID-19 risk, providing a holistic measure that encompasses the collective impact of hazards and exposure, socio-economic vulnerability, and the lack of coping capacity. These interconnected risk categories, as depicted in the Bayesian Influence Diagram (BID) model illustrated in Figure 5, collectively shape the landscape of COVID-19 vaccination uptake decision utility in Pakistan.

As shown in Figure 5, the values for risk dimensions and total risk were derived from conditional probability tables by assessing the impact of associated factors on the likelihood and severity of risks. Through propagating these probabilities, risk values ranging from 0 to 100 were calculated, with each percentage reflecting the degree of risk associated with specific dimensions or the overall risk. These values serve as baselines, representing the initial assessment of risk based on factors such as hazard exposure, socio-economic vulnerability, and lack of coping capacity. The results of total COVID-19 risk underscore the prominence of two major risk components: hazards and exposure and lack of coping capacity, which substantially influence decision-making regarding COVID-19 vaccination uptake. While socio-economic vulnerability also contributes to shaping vaccination decisions, its impact is comparatively lower than that of the other two risk dimensions. This nuanced understanding of the various risk components is pivotal for policymakers aiming to devise targeted strategies to address the multifaceted challenges posed by the pandemic effectively.

In the provincial context, Figure S1 delves into the specific risk exposures across Sindh, Punjab, Baluchistan, and KPK. Sindh emerges as the province facing the highest risk at 41%, followed by Punjab (26%), Baluchistan (25%), and KPK (22%). For instance, in Sindh, where densely populated urban areas like Karachi are prevalent, the risk of COVID-19 transmission may be higher due to population density and mobility. In contrast, KPK, with its more rural landscape, may have lower transmission rates due to less dense populations and lower mobility. Notably, the expected utility of vaccination uptake decisions varies across provinces, with Sindh exhibiting a higher utility value than KPK. This nuanced provincial disparity emphasizes the need for tailored interventions, suggesting that policymakers should prioritize controlling the spread of COVID-19 more intensively in Sindh compared to other provinces.

Figure 5A–D reveals positive vaccination uptake across all provinces. This positive interpretation signifies that implementing vaccination enforcement policies can effectively empower provincial governments to combat the challenges posed by the coronavirus pandemic. For example, in Punjab, where there are significant urban centers like Lahore and Faisalabad, strict enforcement of vaccination policies can help curb transmission rates and protect vulnerable populations. The findings endorse the utility of vaccination as a strategic tool in the arsenal against COVID-19, emphasizing its potential effectiveness in curbing the spread of the virus and mitigating its impact on diverse regional landscapes. These findings underscore the dynamic interplay of risk components in the context of COVID-19 across provinces in Pakistan. Policymakers are encouraged to adopt a nuanced approach, recognizing the varying degrees of risk exposure and tailoring interventions to address the unique challenges faced by each province. The positive utility values affirm the potential efficacy of vaccination enforcement policies, providing a beacon of hope in the collective effort to navigate and overcome the complexities of the ongoing pandemic.

5. Conclusions

This paper presents Bayesian Influence Diagrams (BIDs) to solve the complex problem of COVID-19 vaccination policy decision-making. Two routes of risk assessment decision-making are studied: enforcing vaccination or not. The study identified 29 risk factors for hazard and exposure, socio-economic vulnerability, and lack of coping capacity. Coronavirus vaccination decision utility was studied for all four provinces of Pakistan. The interdependencies of causal relationships in COVID-19 vaccination uptake decisions have never been studied. This challenge was overcome by expert elicitation, and the risk data in this research were adopted from the literature. Then, this study conceptualized and operationalized a data-driven process combining expert elicitation techniques for capturing and assessing the network-wide importance of multidimensional factors influencing COVID-19 vaccination uptake decision utility.

The real contribution of this piece lies in its innovative approach to addressing vaccine hesitancy by utilizing the INFORM COVID-19 risk warning model. Unlike previous studies that have primarily focused on general factors (demographic factors, accessibility, and cost, personal responsibility and risk perceptions, preventive measures, safety and efficacy of a new vaccine, vaccine misinformation, etc.) for the assessment of vaccine hesitancy, this study pioneers the use of a theoretical model to quantify the propagation impact of three key risk categories: hazard and exposure, socio-economic vulnerability, and lack of coping capacity. This research provides valuable insights into the complex dynamics underlying vaccine hesitancy by quantifying the influence of these risk categories and their associated factors on vaccination uptake policy decisions. By incorporating a rigorous analytical framework, this study advances our understanding of the factors contributing to vaccine hesitancy. It offers practical implications for policymakers and public health authorities seeking to develop effective vaccination strategies. Overall, integrating the INFORM COVID-19 risk warning model with quantitative analysis represents a significant contribution to the public health field, with the potential to inform evidence-based policy decision-making and improve vaccine uptake rates in the country.

The results show that the health system of Sindh province in Pakistan has the highest exposure to COVID-19 hazards, and Punjab has the weakest health system for coping with the coronavirus situation. The health system of Punjab province also faces the most socio-economic vulnerability due to COVID-19. Due to a slightly better health system, the study finds that the KPK province has the least COVID-19 risk. The hazard and exposure findings show that the population size in urban and rural areas with seasonal variations (cold winter and hot summer) influences the utility of COVID-19 vaccination. The socioeconomic vulnerability findings highlight that household characteristics are affected by several primary factors: Household economic situation, fear of using health facilities due to the spread of COVID-19, lack of public transportation services, food insecurity, a temporary halt in education, and weak governance affect the vaccination utility. The lack of coping capacity results show that the government's financial assistance and development of digital platforms raised digital health literacy and increased vaccination utility. The results of total COVID-19 risk ascertain that hazard and exposure and lack of coping capacity significantly impact vaccination uptake decision utility compared to socio-economic vulnerability. However, this study concluded that the government's firm vaccine uptake decisions positively affect four provinces of Pakistan.

The proposed approach can assist policymakers in developing appropriate strategies to view network-wide epidemic risks that influence vaccine uptake decisions. Also, by understanding the characteristics of different populations and the factors that affect vaccination uptake, evidence-based multilevel interventions can be planned to enhance vaccine uptake rates in Pakistan and other countries where policymakers face similar issues.

The implications of this research's contributions for other countries are substantial, as it offers valuable insights and strategies to address vaccine hesitancy and improve vaccination uptake rates globally. Other countries can adopt and adapt the INFORM COVID-19 risk warning model for specific contexts. By leveraging such models, policymakers can better understand the multifaceted nature of vaccine hesitancy and tailor intervention strategies accordingly. Countries can conduct quantitative analyses similar to the one described in the research to assess the propagation impact of different risk categories on vaccination uptake. This approach allows for a systematic evaluation of the factors influencing vaccine hesitancy and can inform targeted interventions. Insights from the research can guide policymakers in formulating evidence-based vaccination policies and strategies. By understanding the relative importance of hazard and exposure, socio-economic vulnerability, and lack of coping capacity, countries can prioritize interventions that address the most significant barriers to vaccine uptake within their populations. Countries can develop strategies to mitigate socio-economic vulnerabilities that contribute to vaccine hesitancy. It may involve implementing targeted outreach programs, addressing healthcare access disparities, and supporting marginalized communities. Strengthening coping capacity can include investments in healthcare infrastructure, enhancing public health communication and education, and fostering community resilience. By building robust systems for pandemic preparedness and response, countries can better manage future health crises and mitigate the impact of vaccine hesitancy. These research implications extend beyond the specific context described in the study and offer valuable guidance for countries worldwide seeking to overcome vaccine hesitancy and achieve higher vaccination uptake rates. By implementing evidence-based strategies informed by quantitative analysis and risk assessment models, countries can enhance their public health response to the COVID-19 pandemic and future health challenges.

The proposed approach is flexible and repeatable and can be used to evaluate the effectiveness of policy instruments, e.g., vaccination enforcement programs, to improve prevention, preparedness, and mitigation against pandemics. However, this study has some limitations. The comparison of this study's outcome with those of similar studies was difficult because literature was not available to make quantitative risk assessments on COVID-19 vaccination enforcement policy decisions.

This study's scope is limited concerning comparing state interventions across different vaccines. Specifically, the study concentrates on COVID-19 vaccine situations, driven by their immediate relevance and urgency. This focus makes it difficult to thoroughly examine state interventions across various vaccines, such as flu and polio. Nonetheless, the study suggests that future research endeavors could delve into this area by conducting comparative analyses of state intervention and vaccination outcomes across diverse vaccine contexts, encompassing flu and other vaccines with varying government involvement. Acknowledging this limitation opens up an important avenue for future investigation, providing an opportunity to deepen our understanding of the factors influencing vaccination decisions and outcomes in various settings.

Furthermore, some areas of the INFORM COVID-19 risk were not fully or partially covered. This study used only INFORM risk dimensions (hazards and exposure, socio-economic vulnerability, and lack of coping capacity) for risk assessment while using limited open-source data to assess their impact on vaccine uptake policy decisions. This study was constrained by the need for more local (provincial) data; therefore, not all factors could be evaluated. We recommend adding multidimensional factors to future works to develop an effective decision support system.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/systems12050167/s1, Figure S1: Provincial-level comparison of COVID-19 risk and its associated dimensions; Table S1: INFORM COVID-19 risk categories and context-specific risk factors.

Author Contributions: Conceptualization, H.W.A., Z.S. and U.D.; methodology, H.W.A. and Z.S.; software, H.W.A.; validation, H.W.A., Z.S. and U.D.; formal analysis, H.W.A. and Z.S.; investigation, H.W.A.; resources, H.W.A., Z.S. and U.D.; data curation, H.W.A.; writing—original draft preparation, H.W.A. and Z.S.; writing—review and editing, H.W.A., Z.S. and U.D.; visualization, H.W.A., Z.S. and U.D.; supervision, Z.S.; project administration, Z.S.; funding acquisition, U.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. The APC was funded by Memorial University of Newfoundland, Canada.

Data Availability Statement: Available upon request.

Acknowledgments: All authors thank the Queen Elizabeth II Library (Serials and Acquisitions Department) of Memorial University of Newfoundland, Canada, for their generous financial support in covering the Open Access APC for this paper.

Conflicts of Interest: The authors declare no potential conflicts of interest.

References

1. Agarwal, R.; Gopinath, G.; Farrar, J.; Hatchett, R.; Sands, P. *A Global Strategy to Manage the Long-Term Risks of COVID-19*; IMF Working Papers; IMF Publications: Washington, DC, USA, 2022.
2. Sajid, Z. A dynamic risk assessment model to assess the impact of the coronavirus (COVID-19) on the sustainability of the biomass supply chain: A case study of a US biofuel industry. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111574. [CrossRef] [PubMed]
3. Al-Hasan, A.; Khuntia, J.; Yim, D. Does seeing what others do through social media influence vaccine uptake and help in herd immunity through vaccination? A cross-sectional analysis. *Front. Public Health* **2021**, *9*, 715931. [CrossRef] [PubMed]
4. Andersson, P.A.; Tinghög, G.; Västfjäll, D. The effect of herd immunity thresholds on willingness to vaccinate. *Humanit. Soc. Sci. Commun.* **2022**, *9*, 243. [CrossRef] [PubMed]

5. Forman, R.; Shah, S.; Jeurissen, P.; Jit, M.; Mossialos, E. COVID-19 vaccine challenges: What have we learned so far and what remains to be done? *Health Policy* **2021**, *125*, 553–567. [CrossRef] [PubMed]
6. Yahia, A.I.O.; Alshahrani, A.M.; Alsulmi, W.G.H.; Alqarni, M.M.M.; Abdulrahim, T.K.A.; Heba, W.F.H.; Alqarni, T.A.A.; Alharthi, K.A.Z.; Buhran, A.A.A. Determinants of COVID-19 vaccine acceptance and hesitancy: A cross-sectional study in Saudi Arabia. *Hum. Vaccines Immunother.* **2021**, *17*, 4015–4020. [CrossRef]
7. Valckx, S.; Crèvecoeur, J.; Verelst, F.; Vranckx, M.; Hendrickx, G.; Hens, N.; Van Damme, P.; Pepermans, K.; Beutels, P.; Neyens, T. Individual factors influencing COVID-19 vaccine acceptance in between and during pandemic waves (July–December 2020). *Vaccine* **2022**, *40*, 151–161. [CrossRef] [PubMed]
8. Giannouchos, T.V.; Steletou, E.; Saridi, M.; Souliotis, K. Mandatory vaccination support and intentions to get vaccinated for COVID-19: Results from a nationally representative general population survey in October 2020 in Greece. *J. Eval. Clin. Pract.* **2021**, *27*, 996–1003. [CrossRef] [PubMed]
9. Baden, L.R.; El Sahly, H.M.; Essink, B.; Kotloff, K.; Frey, S.; Novak, R.; Diemert, D.; Spector, S.A.; Rouphael, N.; Creech, C.B.; et al. Efficacy and safety of the mRNA-1273 SARS-CoV-2 vaccine. *N. Engl. J. Med.* **2020**, *384*, 403–416. [CrossRef] [PubMed]
10. Wu, Z.; Hu, Y.; Xu, M.; Chen, Z.; Yang, W.; Jiang, Z.; Li, M.; Jin, H.; Cui, G.; Chen, P.; et al. Safety, tolerability, and immunogenicity of an inactivated SARS-CoV-2 vaccine (CoronaVac) in healthy adults aged 60 years and older: A randomised, double-blind, placebo-controlled, phase 1/2 clinical trial. *Lancet Infect. Dis.* **2021**, *21*, 803–812. [CrossRef]
11. Amit, S.; Regev-Yochay, G.; Afek, A.; Kreiss, Y.; Leshem, E. Early rate reductions of SARS-CoV-2 infection and COVID-19 in BNT162b2 vaccine recipients. *Lancet* **2021**, *397*, 875–877. [CrossRef]
12. Haas, E.J.; Angulo, F.J.; McLaughlin, J.M.; Anis, E.; Singer, S.R.; Khan, F.; Brooks, N.; Smaja, M.; Mircus, G.; Pan, K.; et al. Impact and effectiveness of mRNA BNT162b2 vaccine against SARS-CoV-2 infections and COVID-19 cases, hospitalisations, and deaths following a nationwide vaccination campaign in Israel: An observational study using national surveillance data. *Lancet* **2021**, *397*, 1819–1829. [CrossRef]
13. Hall, V.J.; Foulkes, S.; Charlett, A.; Atti, A.; Monk, E.J.; Simmons, R.; Wellington, E.; Cole, M.J.; Saei, A.; Oguti, B.; et al. SARS-CoV-2 infection rates of antibody-positive compared with antibody-negative healthcare workers in England: A large, multicentre, prospective cohort study (SIREN). *Lancet* **2021**, *397*, 1459–1469. [CrossRef]
14. Khalife, J.; VanGennep, D. COVID-19 herd immunity in the absence of a vaccine: An irresponsible approach. *Epidemiol. Health* **2021**, *43*, e2021012. [CrossRef] [PubMed]
15. Lacsa, J.E.M.; Cordero, D.A., Jr. We are here... so where's the vaccine? Achieving 'herd immunity in the midst of the COVID-19 pandemic. *J. Public Health* **2021**, *43*, e533–e534. [CrossRef]
16. MacIntyre, C.R.; Costantino, V.; Trent, M. Modelling of COVID-19 vaccination strategies and herd immunity, in scenarios of limited and full vaccine supply in NSW, Australia. *Vaccine* **2022**, *40*, 2506–2513. [CrossRef]
17. Peters, M.D. Addressing vaccine hesitancy and resistance for COVID-19 vaccines. *Int. J. Nurs. Stud.* **2022**, *131*, 104241. [CrossRef]
18. Hotez, P.J.; Cooney, R.E.; Benjamin, R.M.; Brewer, N.T.; Buttenheim, A.M.; Callaghan, T.; Caplan, A.; Carpiano, R.M.; Clinton, C.; DiResta, R.; et al. Announcing the Lancet Commission on vaccine refusal, acceptance, and demand in the USA. *Lancet* **2021**, *397*, 1165–1167. [CrossRef] [PubMed]
19. Freeman, D.; Loe, B.S.; Chadwick, A.; Vaccari, C.; Waite, F.; Rosebrock, L.; Jenner, L.; Petit, A.; Lewandowsky, S.; Vanderslott, S.; et al. COVID-19 vaccine hesitancy in the UK: The Oxford coronavirus explanations, attitudes, and narratives survey (Oceans) II. *Psychol. Med.* **2022**, *52*, 3127–3141. [CrossRef]
20. Geoghegan, S.; O'Callaghan, K.P.; Offit, P.A. Vaccine safety: Myths and misinformation. *Front. Microbiol.* **2020**, *11*, 372. [CrossRef]
21. Shen, A. Finding a way to address a wicked problem: Vaccines, vaccination, and a shared understanding. *Hum. Vaccines Immunother* **2020**, *16*, 1030–1033. [CrossRef]
22. Butter, S.; McGlinchey, E.; Berry, E.; Armour, C. Psychological, social, and situational factors associated with COVID-19 vaccination intentions: A study of UK key workers and non-key workers. *Br. J. Health Psychol.* **2022**, *27*, 13–29. [CrossRef]
23. WHO. *Report of the SAGE Working Group on Vaccine Hesitancy*; World Health Organization: Geneva, Switzerland, 2014; p. 64.
24. Biswas, M.R.; Alzubaidi, M.S.; Shah, U.; Abd-Alrazaq, A.A.; Shah, Z. A scoping review to find out worldwide COVID-19 vaccine hesitancy and its underlying determinants. *Vaccines* **2021**, *9*, 1243. [CrossRef] [PubMed]
25. Dubé, E.; Gagnon, D.; Nickels, E.; Jeram, S.; Schuster, M. Mapping vaccine hesitancy—Country-specific characteristics of a global phenomenon. *Vaccine* **2014**, *32*, 6649–6654. [CrossRef]
26. Al-Amer, R.; Maneze, D.; Everett, B.; Montayre, J.; Villarosa, A.R.; Dwekat, E.; Salamonson, Y. COVID-19 vaccination intention in the first year of the pandemic: A systematic review. *J. Clin. Nurs.* **2022**, *31*, 62–86. [CrossRef] [PubMed]
27. AlShurman, B.A.; Khan, A.F.; Mac, C.; Majeed, M.; Butt, Z.A. What demographic, social, and contextual factors influence the intention to use COVID-19 vaccines: A scoping review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 9342. [CrossRef] [PubMed]
28. Al-Jayyousi, G.F.; Sherbash, M.A.M.; Ali, L.A.M.; El-Heneidy, A.; Alhussaini, N.W.Z.; Elhassan, M.E.A.; Nazzal, M.A. Factors influencing public attitudes towards COVID-19 vaccination: A scoping review informed by the socio-ecological model. *Vaccines* **2021**, *9*, 548. [CrossRef] [PubMed]
29. Lazarus, J.V.; Wyka, K.; White, T.M.; Picchio, C.A.; Rabin, K.; Ratzan, S.C.; Leigh, J.P.; Hu, J.; El-Mohandes, A. Revisiting COVID-19 vaccine hesitancy around the world using data from 23 countries in 2021. *Nat. Commun.* **2022**, *13*, 3801. [CrossRef] [PubMed]

30. Moola, S.; Gudi, N.; Nambiar, D.; Dumka, N.; Ahmed, T.; Sonawane, I.R.; Kotwal, A. A rapid review of evidence on the determinants of and strategies for COVID-19 vaccine acceptance in low and middle-income countries. *J. Glob. Health* **2021**, *11*, 05027. [CrossRef] [PubMed]
31. Solís Arce, J.S.; Warren, S.S.; Meriggi, N.F.; Scacco, A.; McMurry, N.; Voors, M.; Syunyaev, G.; Malik, A.A.; Aboutajdine, S.; Adeojo, O.; et al. COVID-19 vaccine acceptance and hesitancy in low-and middle-income countries. *Nat. Med.* **2021**, *27*, 1385–1394. [CrossRef]
32. Roy, D.N.; Biswas, M.; Islam, E.; Azam, S. Potential factors influencing COVID-19 vaccine acceptance and hesitancy: A systematic review. *PLoS ONE* **2022**, *17*, e0265496. [CrossRef]
33. Fajar, J.K.; Sallam, M.; Soegiarto, G.; Sugiri, Y.J.; Anshory, M.; Wulandari, L.; Kosasih, S.A.P.; Ilmawan, M.; Kusnaeni, K.; Fikri, M.; et al. Global Prevalence and Potential Influencing Factors of COVID-19 Vaccination Hesitancy: A Meta-Analysis. *Vaccines* **2022**, *10*, 1356. [CrossRef] [PubMed]
34. Poljansek, K.; Vernaccini, L.; Dalla Valle, D.; Orenaike, O.; Galimberti, L. *INFORM Covid-19 Warning Tool: Concept and Methodology*; Publications Office of the European Union: Kirchberg, Luxembourg, 2021.
35. Peleg, K.; Bodas, M.; Hertelendy, A.J.; Kirsch, T.D. The COVID-19 pandemic challenge to the All-Hazards Approach for disaster planning. *Int. J. Disaster Risk Reduct.* **2021**, *55*, 102103. [CrossRef]
36. Petroni, M.; Hill, D.; Younes, L.; Barkman, L.; Howard, S.; Howell, I.B.; Mirowsky, J.; Collins, M.B. Hazardous air pollutant exposure as a contributing factor to COVID-19 mortality in the United States. *Environ. Res. Lett.* **2020**, *15*, 0940a9. [CrossRef]
37. Chaudhary, M.T.; Piracha, A. Natural disasters—Origins, impacts, management. *Encyclopedia* **2021**, *1*, 1101–1131. [CrossRef]
38. Duvat, V.K.; Volto, N.; Stahl, L.; Moatty, A.; Defossez, S.; Desarthe, J.; Grancher, D.; Pillet, V. Understanding interlinkages between long-term trajectory of exposure and vulnerability, path dependency and cascading impacts of disasters in Saint-Martin (Caribbean). *Glob. Environ. Chang.* **2021**, *67*, 102236. [CrossRef]
39. Sam, P. Redefining vulnerability in the era of COVID-19. *Lancet* **2020**, *395*, 1089.
40. Chen, Y.; Klein, S.L.; Garibaldi, B.T.; Li, H.; Wu, C.; Osevala, N.M.; Li, T.; Margolick, J.B.; Pawelec, G.; Leng, S.X. Aging in COVID-19: Vulnerability, immunity and intervention. *Ageing Res. Rev.* **2021**, *65*, 101205. [CrossRef]
41. Tavares, F.F.; Betti, G. The pandemic of poverty, vulnerability, and COVID-19: Evidence from a fuzzy multidimensional analysis of deprivations in Brazil. *World Dev.* **2021**, *139*, 105307. [CrossRef]
42. Capano, G.; Howlett, M.; Jarvis, D.S.; Ramesh, M.; Goyal, N. Mobilizing policy (in) capacity to fight COVID-19: Understanding variations in state responses. *Policy Soc.* **2020**, *39*, 285–308. [CrossRef] [PubMed]
43. Baniamin, H.M.; Rahman, M.; Hasan, M.T. The COVID-19 pandemic: Why are some countries coping more successfully than others? *Asia Pac. J. Public Adm.* **2020**, *42*, 153–169. [CrossRef]
44. Serikbayeva, B.; Abdulla, K.; Oskenbayev, Y. State capacity in responding to COVID-19. *Int. J. Public Adm.* **2021**, *44*, 920–930. [CrossRef]
45. Ferguson, N. Capturing human behaviour. *Nature* **2007**, *446*, 733. [CrossRef] [PubMed]
46. Tomassen, F.; de Koeijer, A.; Mourits, M.; Dekker, A.; Bouma, A.; Huirne, R. A decision-tree to optimise control measures during the early stage of a foot-and-mouth disease epidemic. *Prev. Vet. Med.* **2002**, *54*, 301–324. [CrossRef] [PubMed]
47. Sok, J.; Hogeveen, H.; Elbers, A.; Velthuis, A.; Lansink, A.O. Expected utility of voluntary vaccination in the middle of an emergent Bluetongue virus serotype 8 epidemic: A decision analysis parameterized for Dutch circumstances. *Prev. Vet. Med.* **2014**, *115*, 75–87. [CrossRef] [PubMed]
48. Karnon, J. *A Simple Decision Analysis of a Mandatory Lockdown Response to the COVID-19 Pandemic*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 329–331.
49. Tharwani, Z.H.; Kumar, P.; Marfani, W.B.; Shaeen, S.K.; Adnan, A.; Mohanan, P.; Islam, Z.; Essar, M.Y. What has been learned about COVID-19 vaccine hesitancy in Pakistan: Insights from a narrative review. *Health Sci. Rep.* **2022**, *5*, e940. [CrossRef]
50. Butt, M.; Mohammed, R.; Butt, E.; Butt, S.; Xiang, J. Why have immunization efforts in Pakistan failed to achieve global standards of vaccination uptake and infectious disease control? *Risk Manag. Healthc. Policy* **2020**, *13*, 111. [CrossRef] [PubMed]
51. Jamal, D.; Zaidi, S.; Husain, S.; Orr, D.W.; Riaz, A.; Farrukhi, A.A.; Najmi, R. Low vaccination in rural Sindh, Pakistan: A case of refusal, ignorance or access? *Vaccine* **2020**, *38*, 4747–4754. [CrossRef] [PubMed]
52. Perveen, S.; Akram, M.; Nasar, A.; Arshad-Ayaz, A.; Naseem, A. Vaccination-hesitancy and vaccination-inequality challenges in Pakistan's COVID-19 response. *J. Community Psychol.* **2022**, *50*, 666–683. [CrossRef]
53. Sajid, Z.; Khan, F.; Zhang, Y. Integration of interpretive structural modelling with Bayesian network for biodiesel performance analysis. *Renew. Energy* **2017**, *107*, 194–203. [CrossRef]
54. Dao, U.; Sajid, Z.; Khan, F.; Zhang, Y. Safety analysis of blended hydrogen pipelines using dynamic object-oriented bayesian network. *Int. J. Hydrog. Energy* **2024**, *52*, 841–856. [CrossRef]
55. PBS. *Pakistan Social And Living Standards Measurement Survey*; Government of Pakistan: Islamabad, Pakistan, 2021.
56. PBS. *Special Survey for Evaluating Socio-Economic Impact of COVID-19 on Wellbeing of People 2020*; Pakistan Bureau of Statistics: Islamabad, Pakistan, 2020.
57. PBS. *Salient Features—6th Population & Housing Census 2017*; Government of Pakistan: Islamabad, Pakistan, 2017.
58. PBS. *Pakistan Demographic Survey (PDS)*; Government of Pakistan: Islamabad, Pakistan, 2006.
59. NCOC. *Current Laboratory Testing Capacity for COVID-19 In Pakistan*; Government of Pakistan: Islamabad, Pakistan, 2021.
60. NCOC. *List of Province-Wise Quarantine Facilities in Pakistan*; Government of Pakistan: Islamabad, Pakistan, 2021.

61. NCOC. *PAK COVID-19 Vaccination Pass App*; Government of Pakistan: Islamabad, Pakistan, 2021.
62. NCOC. *National Immunization Management System*; Government of Pakistan: Islamabad, Pakistan, 2021.
63. Hemming, V.; Burgman, M.A.; Hanea, A.M.; McBride, M.F.; Wintle, B.C. A practical guide to structured expert elicitation using the IDEA protocol. *Methods Ecol. Evol.* **2018**, *9*, 169–180. [CrossRef]
64. Schmidt, O.; Gambhir, A.; Staffell, I.; Hawkes, A.; Nelson, J.; Few, S. Future cost and performance of water electrolysis: An expert elicitation study. *Int. J. Hydrog. Energy* **2017**, *42*, 30470–30492. [CrossRef]
65. Jensen, F.V.; Nielsen, T.D. *Bayesian Networks, and Decision Graphs*; Springer: Berlin/Heidelberg, Germany, 2007; Volume 2.
66. Zhang, L.W.; Guo, H.P. *Introduction to Bayesian Networks*; China Science Publishing & Media Ltd. (CSPM): Beijing, China, 2006.
67. Arlot, S.; Celisse, A. A survey of cross-validation procedures for model selection. *Stat. Surv.* **2010**, *4*, 40–79. [CrossRef]
68. Marcot, B.G.; Hanea, A.M. What is an optimal value of k in k-fold cross-validation in discrete Bayesian network analysis? *Comput. Stat.* **2021**, *36*, 2009–2031. [CrossRef]
69. Durr-e-Nayab, N.U.H. *PIDE COVID-19 E-Book*; Pakistan Institute of Development Economics (PIDE): Islamabad, Pakistan, 2020.
70. NCOC. *List of COVID-19 Designated Tertiary Hospitals in Pakistan*; Government of Pakistan: Islamabad, Pakistan, 2021.