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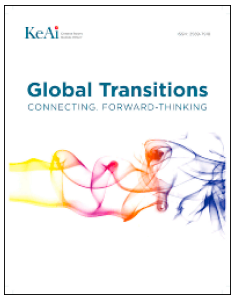

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Assessing the Impact of Sustainability Risks on Disaster and Pandemic Vulnerabilities: A Global Perspective

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Abstract

This study examines the impact of failing to achieve Sustainable Development Goals (SDGs) on disaster and pandemic vulnerabilities, providing a country-level perspective to inform resilience planning. The study introduces the concept of SDG-related risk, defined as the probability of not achieving the desired SDG, and classifies these risks into three categories: high, medium, and low. Using a Bayesian Belief Network (BBN) framework, two probabilistic models were developed to evaluate the influence of SDG performance on disaster risk and COVID-19 vulnerability across 165 countries. The results highlight that shortcomings in SDGs such as 'quality education', 'sustainable cities and communities', 'no poverty', and 'affordable and clean energy' significantly increase disaster and pandemic risks. Conversely, strong performance in 'peace, justice, and strong institutions' and 'life on land' enhances systemic resilience, reducing vulnerability. Countries with very high disaster risk are particularly exposed to deficiencies in SDGs related to 'peace, justice, and strong institutions', 'sustainable cities and communities', and 'good health and well-being'. For COVID-19 risk, 'affordable and clean energy' emerges as the most critical SDG influencing high-risk exposure, whereas 'climate action' is pivotal in predicting low-risk states. These findings demonstrate the cascading risks posed by failing to achieve critical SDGs and emphasize the need for targeted interventions to mitigate vulnerabilities to disasters and pandemics, providing actionable insights for sustainable resilience strategies.

Keywords: Bayesian Belief Network; COVID-19; disaster; resilience; risk; sustainability.

1. Introduction

The UN General Assembly regularly promotes the recognition of a wide range of social and economic policy aims across its member countries, resulting in the 2015 adoption of 17 Sustainable Development Goals (SDGs). These goals are broadly classified into economic, social, and environmental dimensions of sustainability [1]. The 2021 Sustainable Development Report builds on this framework by evaluating the performance of 165 countries across all facets of sustainability. This report presented an aggregate performance score on an index scale of 0 to 100, with 100 representing the best possible performance [2]. Based on data from the United Nations, World Bank, and other research institutions, it includes a dashboard that enables national policymakers to track their country's progress. By visualizing progress on the 17 SDGs, it provides a practical tool for designing effective strategies to achieve these goals. Comprehensive methodological details can be found at www.sdgindex.org.

Beyond monitoring progress, achieving the SDGs requires a risk-informed approach to policymaking. The 2030 Global Development Agenda—including the Sendai Framework for Disaster Risk Reduction, the 2030 Agenda for Sustainable Development, and the Paris Agreement—underscores the critical interplay between disaster risk management, sustainable development, and climate risk management [3]. The Sendai Framework, in particular, offers seven global targets supported by guiding principles that aim to reduce the impact of disasters [4]. Recognizing these interconnections is essential, as effective risk management strategies are key to sustainable development progress [5].

Nature-induced disasters can significantly impact sustainable development by undermining economic growth and social progress [6]. The frequency and intensity of natural hazards are

increasing due to the impact of climate change, which in turn can impact sustainable development across various sectors [7]. Likewise, the COVID-19 pandemic, classified as a nature-induced hazard [8], has disrupted economic and social systems globally, requiring every government to formulate effective strategies regarding sustainable development and economic growth [9]. Addressing such complex and interconnected challenges requires a comprehensive risk assessment framework that accounts for socioeconomic, technological, environmental, health, safety, and governance factors [10].

The failure to meet SDGs further magnifies disaster and pandemic risks, creating a vicious cycle. Unmet goals in poverty alleviation, healthcare access, education, and infrastructure development perpetuate socio-economic inequalities and vulnerabilities [1]. Communities lacking these critical resources are less equipped to cope with disasters and pandemics [11]. For example, inadequate healthcare and education systems hinder effective responses, while economic disparities aggravate social unrest and conflicts, further disrupting disaster and health crisis management [12]. Therefore, failing to achieve SDGs not only undermines global development but also increases the susceptibility of populations to disasters and health emergencies.

To break this cycle, governments and stakeholders must place disaster risk reduction at the heart of sustainable development efforts. Strengthening the interface between development and disaster risk management is crucial for building a resilient and sustainable society [3]. This calls for tackling the fundamental drivers of disaster risk and creating unified approaches that combine risk mitigation, resilience strengthening, climate adaptation, and sustainable growth [13].

Aligning these approaches with SDG targets can help build integrated strategies that simultaneously address disaster risks and broader sustainability challenges [5].

This study addresses these challenges by examining the relationship between SDG achievement and vulnerability to disasters and pandemics. It aims to answer three key questions: (1) How does the failure to meet specific SDGs contribute to increased disaster and pandemic risks? (2) What are the interdependencies among SDGs that influence risk exposure? (3) How can a probabilistic network framework be employed to quantify these relationships? By assessing the impact of unmet SDGs on disaster and pandemic vulnerabilities, this study contributes to the literature by operationalizing the risk-resilience-sustainability nexus and offering a novel analytical approach to evaluate the systemic risks posed by SDG failures.

Effectively analyzing these complex relationships demands a systematic approach. The 2030 Agenda consists of 17 interconnected goals, meaning that prioritizing individual goals in isolation can lead to unintended consequences and even jeopardize the agenda's success [14]. While previous studies have modeled the interdependency among SDGs [1, 14-16], disaster-related risks [12, 17, 18] and COVID-19-related risks [10, 19], there has been limited research that systematically integrates SDG failures within a risk analysis framework. This study fills this gap by using a probabilistic network model to assess how deficiencies in SDG progress contribute to country-level disaster and pandemic risks. By bridging this knowledge gap, the study aims to provide insights for policymakers to enhance resilience and sustainable development planning.

2. Literature review

2.1. Sustainability

In 2015, the United Nations introduced 231 indicators, which aggregated into 17 SDGs, to assess global progress towards sustainable development. Each country's performance on these goals is aggregated into an SDG index, which provides a comprehensive measure of national sustainability efforts. However, policymakers are increasingly recognizing the need to prioritize critical SDGs over others to optimize resource allocation. This prioritization requires a risk-informed approach, ensuring that efforts focus on the most pressing sustainability challenges while maintaining balance across interdependent goals.

A key challenge in sustainability planning is the lack of a comprehensive resilience assessment, despite the 2030 Agenda for Sustainable Development recognizing resilience as a crucial component of sustainability [20]. Resilience is closely tied to achieving various SDGs, such as food security, poverty alleviation, universal education, and improved health and well-being [21]. Understanding these interdependencies is essential, as deficiencies in critical SDGs can increase disaster risks and vulnerabilities, while strong performance in resilience-focused SDGs can mitigate systemic risks.

To optimize performance on interconnected SDGs, policymakers must adopt a systematic approach that maps cause-effect relationships across goals. By identifying synergies and trade-offs, stakeholders can enhance the effectiveness of interventions. For instance, nexus thinking—which examines the interconnections between food, energy, and water (FEW)—helps policymakers prioritize critical risks and guide strategies for achieving related SDGs [22]. Given that sustainability deficits can amplify vulnerability to systemic crises, structured risk

assessments are necessary to identify how deficiencies in SDGs influence disaster and pandemic risks.

Sustainable development, which spans the economic, social, and environmental dimensions, requires dynamic strategies considering long-term trade-offs and implications. Policymakers must understand the broader consequences of strategies, including how they might impact interconnected SDGs and the environment. Rather than a project with a fixed end, sustainable development is an ongoing process that integrates various societal, environmental, and economic aspects [23]. However, despite progress in understanding sustainability, there remains a gap in quantifying how these challenges manifest as disaster and pandemic vulnerabilities, emphasizing the need for further research in SDG-driven risk modeling.

Interdependency modeling remains an underexplored research theme, particularly in the context of SDGs. Studies such as those by Cernev and Fenner [24] have identified foundational SDGs with wide-reaching impacts, including 'no poverty', 'good health and well-being', and 'life below water'. Similarly, Biglari *et al.* [25] highlighted critical SDGs, such as 'industry, innovation, and infrastructure', and 'climate action', based on their network-wide influence. Building on these studies, this research seeks to analyze how deficiencies in SDGs systematically influence disaster and pandemic vulnerabilities, forming the basis for the proposed research hypotheses.

2.2. Sustainability and disaster risk reduction

Three global frameworks - including the 2030 Agenda for Sustainable Development, the Paris Agreement (AKA: Paris Climate Accords), and the Sendai Framework for Disaster Risk Reduction - were introduced in 2015 to guide countries regarding sustainable development and disaster risk

management. However, despite their broad adoption, the implementation of these frameworks at the local level remains inadequate, primarily due to political conflict, administrative challenges, and a lack of coordination between key stakeholders [4].

This implementation gap is particularly evident in disaster risk management, where the practical application of these frameworks is often hindered by systemic constraints. Recent studies have explored the practical applications of these frameworks in managing risks, especially in the context of floods and droughts. For instance, Raikes *et al.* [3] found that while these international agreements are valuable for defining disaster risk management principles, their application is limited by low administrative capacity and policy gaps. This limitation highlights the need for risk-based approaches that systematically link sustainability risks to disaster vulnerabilities.

Kelman [13] calls for integrating climate change within broader disaster risk reduction and sustainable development contexts. This approach helps to bridge gaps between the three frameworks, highlighting the importance of aligning mitigation and adaptation strategies across these areas. Such integration ensures that efforts to address climate risks do not undermine broader development goals. A more holistic strategy is required, as emphasized by Wamsler and Johannessen [26], who stress the importance of recognizing interdependencies among SDGs to foster coordinated disaster risk reduction efforts.

Given the increasing frequency and intensity of global risks, it is vital to adopt a risk-informed approach that integrates disaster risk reduction with sustainable development. This is particularly crucial as the world faces pressing challenges like urbanization, inequality, and environmental degradation [7]. By understanding and addressing the underlying drivers of risk, such as poverty

and environmental degradation, countries can foster resilience and enhance their capacity to manage future crises [27]. To further investigate this link, this study proposes the first hypothesis (H1): Deficiencies in SDGs increase disaster vulnerability at the national level.

To assess this hypothesis, this study employs the INFORM Risk Index developed by an international forum for assessing humanitarian crises and disasters [28]. INFORM was chosen over other comparable indexes, such as ND-GAIN and the Global Risk Index, due to its comprehensive risk conceptualization, which integrates hazard exposure, vulnerability, and lack of coping capacity. Unlike ND-GAIN, which primarily focuses on climate resilience, and the Global Risk Index, which assesses physical exposure, INFORM provides a holistic assessment of systemic risks, making it particularly suitable for analyzing the interplay between sustainability and disaster vulnerabilities [29].

2.3. Sustainability and COVID-19

The COVID-19 pandemic has profoundly disrupted global progress toward achieving the SDGs, highlighting the interconnectedness of sustainability dimensions. The pandemic led to the worst global recession since World War II, severely impacting critical SDGs such as 'zero hunger', 'clean water and sanitation', and 'affordable and clean energy' [9]. The pandemic's cascading effects on the FEW nexus—with disruptions in food production, energy, and water supply—underscore the vulnerability of interconnected systems during crises. This interdependence suggests that deficiencies in SDGs could also systematically increase vulnerability to pandemics.

During lockdowns, various sectors, including community services, energy, and transportation, were paralyzed, further aggravating the crisis. This disruption affected human well-being and

increased economic vulnerability [30]. Moreover, the pandemic has underscored the need for strategic planning and resource allocation to prepare for future health crises. Countries must not only learn from COVID-19 but also strengthen their health systems, focusing on key resources like hospital beds, protection equipment, and ventilators [31]. The pandemic's widespread impact emphasizes the necessity of considering SDG deficiencies when assessing a country's preparedness for future global health crises.

The COVID-19 pandemic has also served as a stress test for the SDGs, revealing the fragility of global sustainability efforts. Studies by Wang and Huang [32] and Fenner and Cernev [33] showed that COVID-19 negatively affected almost all SDGs, highlighting the importance of addressing global risks in an integrated manner. Unsustainable practices within global supply chains also increase the risk of future pandemics, further undermining global sustainability [2]. Building on these insights, this study proposes the second hypothesis (H2): Deficiencies in SDGs increase vulnerability to pandemics at the national level.

2.4. Research gaps

Despite considerable progress in modeling SDG interdependencies [1, 24], there are significant gaps in understanding how SDG risks contribute to disaster and COVID-19 risks. While existing studies have focused on modeling risk-resilience-sustainability connections [5], the relative impact of SDG risks on disaster and pandemic risks remains underexplored. This research aims to bridge this gap by using a BBN modeling approach, which allows for the comprehensive assessment of interdependencies and uncertainties associated with SDG achievement.

Aly *et al.* [34] highlighted that the application of BBNs in SDG modeling is still underexplored, and this study seeks to address this limitation by capturing the complex nature of sustainable development challenges. By establishing rankings of individual SDGs based on their contribution to disaster and COVID-19 risks, this research aims to provide new insights into how countries can effectively prioritize actions within the context of interconnected global risks. Table 1 compares the key features of this study with those of existing research, emphasizing its scope and contributions.

Table 1. Comparison of the key features and methodology of this study with similar research on the interdependencies of SDG risks and their impact on disaster and COVID-19 risks, highlighting unique aspects and contributions.

Article (ordered by publication date)	Modeling Technique	Risk-Resilience-Sustainability Nexus	Network-based Approach	Coverage of all 17 SDGs	COVID-19 Risk Assessment	Impact Assessment of SDG risks on Disaster Risk	Explanatory Assessment of SDGs for Disaster Risk Analysis
This paper	Bayesian Belief Network	✓	✓	✓	✓	✓	✓
Eze and Siegmund [35]	Regression analysis and trend analysis	✓	X	X	X	X	X
Gong *et al.* [36]	Network analysis	X	✓	✓	X	X	X
Issa *et al.* [37]	Network analysis	X	✓	✓	X	X	X
Qazi *et al.* [38]	Bayesian Belief Network	✓	✓	✓	X	X	X
Nilashi *et al.* [39]	Literature review and SWOT analysis	X	X	✓	✓	X	X
Song and Jang [40]	Network analysis	X	✓	✓	X	X	X
Qazi *et al.* [1]	Bayesian Belief Network	✓	✓	✓	X	X	X

Article (ordered by publication date)	Modeling Technique	Risk-Resilience-Sustainability Nexus	Network-based Approach	Coverage of all 17 SDGs	COVID-19 Risk Assessment	Impact Assessment of SDG risks on Disaster Risk	Explanatory Assessment of SDGs for Disaster Risk Analysis
Ameli *et al.* [41]	Fuzzy Cognitive Mapping	X	✓	✓	✓	X	X
Bandari *et al.* [14]	Text Mining	X	✓	✓	X	X	X
Biglari *et al.* [25]	System Dynamics	X	✓	✓	X	X	X
Dawes [15]	Interaction Matrices	X	✓	✓	X	X	X
Khan *et al.* [27]	Disaster Resilience Index	✓	X	X	✓	X	X
Fenner and Cernev [33]	Scenario Analysis	X	X	✓	✓	X	X
Cernev and Fenner [24]	Causal Loop Diagram	✓	✓	✓	X	X	X
DeWit *et al.* [7]	Literature Review and Government Reports	✓	X	✓	✓	X	X
Requejo-Castro *et al.* [16]	Bayesian Belief Network	X	✓	X	X	X	X
Sajjad and Chan [5]	Spatial Risk Mapping	✓	✓	✓	X	✓	X
de Amorim *et al.* [42]	Text Mining	✓	X	X	X	X	X

3. Research methodology

A BBN modeling approach was used to explore the research objectives of this study. BBNs have been prioritized over other techniques in several application areas involving risk and uncertainty [43, 44]. In particular, the graphical interface of BBNs and its backward and forward inferencing features make it possible to simulate, visualize, and analyze several what-if scenarios [45]. Similarly, BBNs have been found to outperform other techniques, such as regression analyses, in their ability to predict a dependent variable [46].

The BBN methodology comprised various stages, including data collection, modeling and validation of BBNs, predictive ability estimation of individual SDG risks, impact assessment of risks associated with SDGs on disaster and COVID-19 risks, and ranking of SDG risks based on their network-wide vulnerability and resilience potential (see Fig. 1). The network-wide vulnerability and resilience potential of an SDG risk represents its negative and positive impact on the interlinked SDG risk network given the worst- and best-case performance scenario of the SDG risk, respectively. Three datasets were collected regarding country-level assessments on sustainability, disaster risk, and COVID-19 risk from INFORM [28, 47] and the SDG report 2021 [2]. The sustainability dataset comprised the SDG performance scores of 165 countries in 2021. Each country was assessed on a scale of 0 to 100 for each SDG, with 0 and 100 representing the worst and best possible performance, respectively. The dataset prioritized countries based on their performance across individual SDGs using four performance categories: goal achievement, challenges remain, significant challenges, and major challenges.

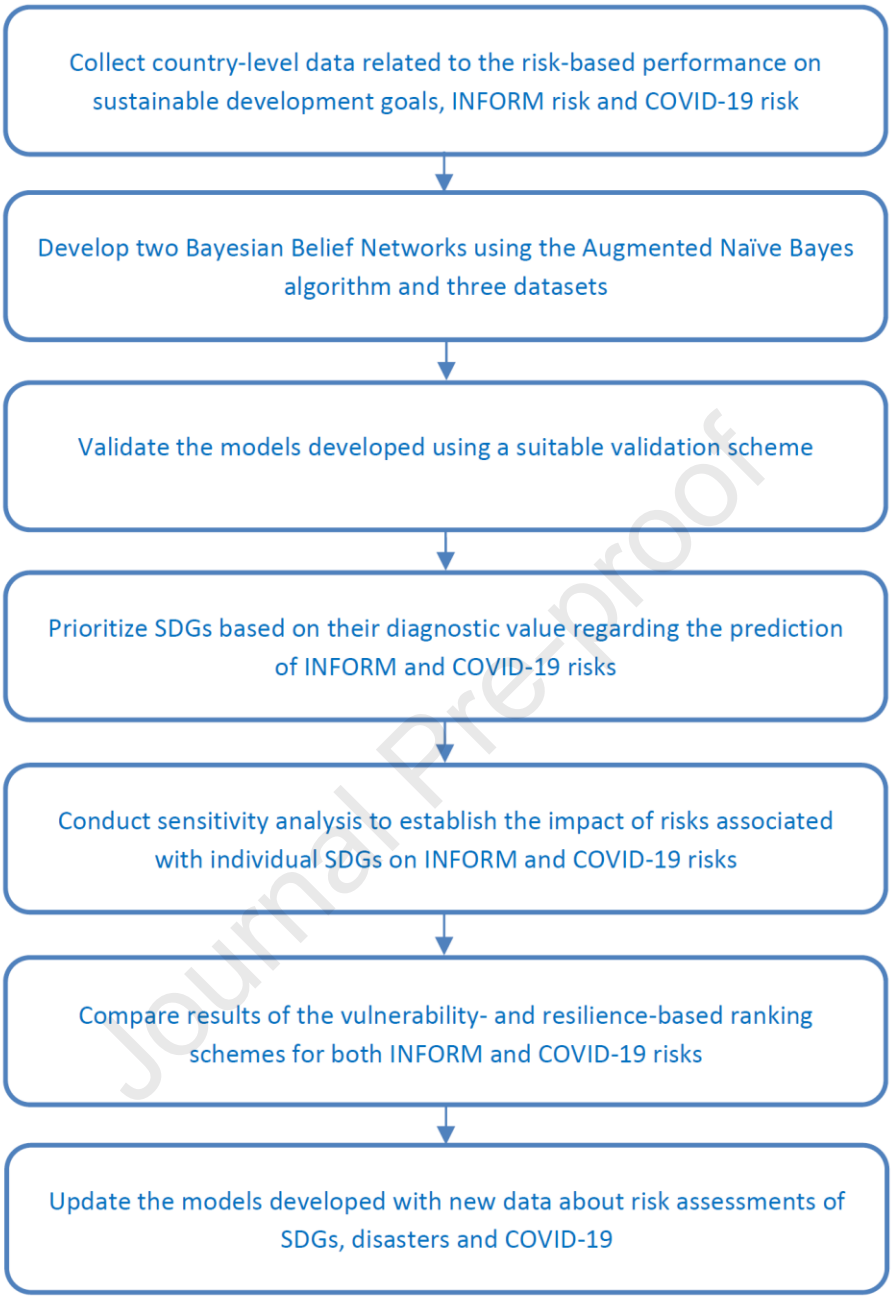


Fig. 1. Modeling process adopted for linking SDGs to disaster and COVID-19 risks.

This study introduces the concept of risk associated with each SDG as the probability of not achieving the desired goal and establishes three states of SDG risk, including high-, medium-, and low-risk. The four categories of SDG performance from the dataset were mapped to the three

risk states such that the 'goals achievement' category was classified as a 'low risk' state and the 'major challenges' category was classified as a 'high' risk state. The remaining two categories were merged and labeled as a 'medium' risk state. An 'unknown' state was introduced to indicate missing values.

Two datasets by INFORM [28, 47] were used for country-level disaster and COVID-19 risk assessments for 2021; these publicly available datasets have been widely used in the literature on disaster and pandemic risk analyses due to their reliability (Haque et al., 2020). The data comprised risk assessments for 191 countries on a scale of 0 to 10 with 10 representing the least desirable value. These 191 countries were then matched with the 165 countries represented in the 2021 Sustainable Development Report for further analysis. The complete dataset has been provided as supplementary material. This study discretized both disaster and COVID-19 risks into five states: very low, low, medium, high, and very high following the approach adopted by INFORM.

A BBN is a graphical model comprising nodes (variables) and arcs, which represent either cause-effect relationships or statistical dependencies [48]. BBNs can be developed using both historical data and expert judgment and they can simulate different what-if scenarios [45]. BBNs have been widely used to model risk and uncertainty across different application areas, including project management [49, 50], supply chain and logistics management [51-54], healthcare [55], and disaster risk management [43]. This study adopts a data-driven BBN modeling approach to map dependencies among SDG risks regarding their impact on disaster and COVID-19 risks given the availability of country-level data on sustainability and disaster/COVID-19 risk. The methodology

adopted to develop and analyze the BBN models for addressing the research objectives of this study followed a structured approach grounded in the literature on BBN modeling [55, 56].

Since the Naive Bayes algorithm restricts the feature variables to have only one parent node (class variable), the Augmented Naive Bayes (ANB) structure learning algorithm is utilized to map dependencies among SDGs for both models. This algorithm performs better than the Naïve Bayes and Tree-Augmented Naïve (TAN) algorithms and there is no restriction on the number of connections (arcs) across feature variables [57].

The data-driven modeling of discrete BBNs involves various steps: discretizing uncertain variables (SDG-related, disaster, and pandemic risks), developing a network structure, and learning (conditional) probability distributions. Several software packages, such as Netica, AgenaRisk, and GeNIe, can be used to develop, validate, and analyze BBN models [55]. Kaikkonen *et al.* [58] provide a comprehensive overview of BBNs and the utility of this technique in environmental risk management.

Using the discretized data for the 17 SDGs and disaster and COVID-19 risk assessments, two BBN models were developed in GeNIe 2.0. Both models were validated using the *k*-fold cross-validation technique, which is considered an effective technique in the literature on BBN modeling [60]. The disaster risk- and COVID-19 risk-related models achieved a prediction accuracy of 73.3% and 89.1%, respectively. SDGs can be ranked based on their risk-based assessment of the actual state of disaster and COVID-19 risks. Cross-entropy – an information-theoretic measure – can be used to rank SDGs based on their diagnostic value regarding disaster and pandemic risks, which represents the expected reduction in entropy (uncertainty) of the

probability distribution over a certain state of disaster/pandemic risk after observing the risk state of an individual SDG. Cross-entropy can help prioritize feature variables based on their ability to predict a target (class) variable [56]. The results and analyses of the two BBN models developed are presented in the next section.

4. Results

The first BBN model represents dependencies among individual SDG risks, with disaster risk representing the class variable (see Fig. 2). The bar chart associated with each risk represents the probability distribution across 165 countries. Some key SDGs can be identified based on their probability of the 'high risk' state. For instance, the 'zero hunger', 'life on land', 'peace, justice and strong institutions', 'life below water', 'good health and well-being' and 'industry, innovation and infrastructure' goals are all exposed to a high-risk level. In the case of disaster risk, 9% (N = 15) of the countries are exposed to a very high level of risk compared to 21% (N = 35) with a very low-risk exposure. Seven critical SDGs, including 'peace, justice and strong institutions', 'no poverty', 'good health and well-being', 'clean water and sanitation', 'industry, innovation and infrastructure', 'partnerships for the goals' and 'sustainable cities and communities', are directly or indirectly connected with multiple SDGs across the network.

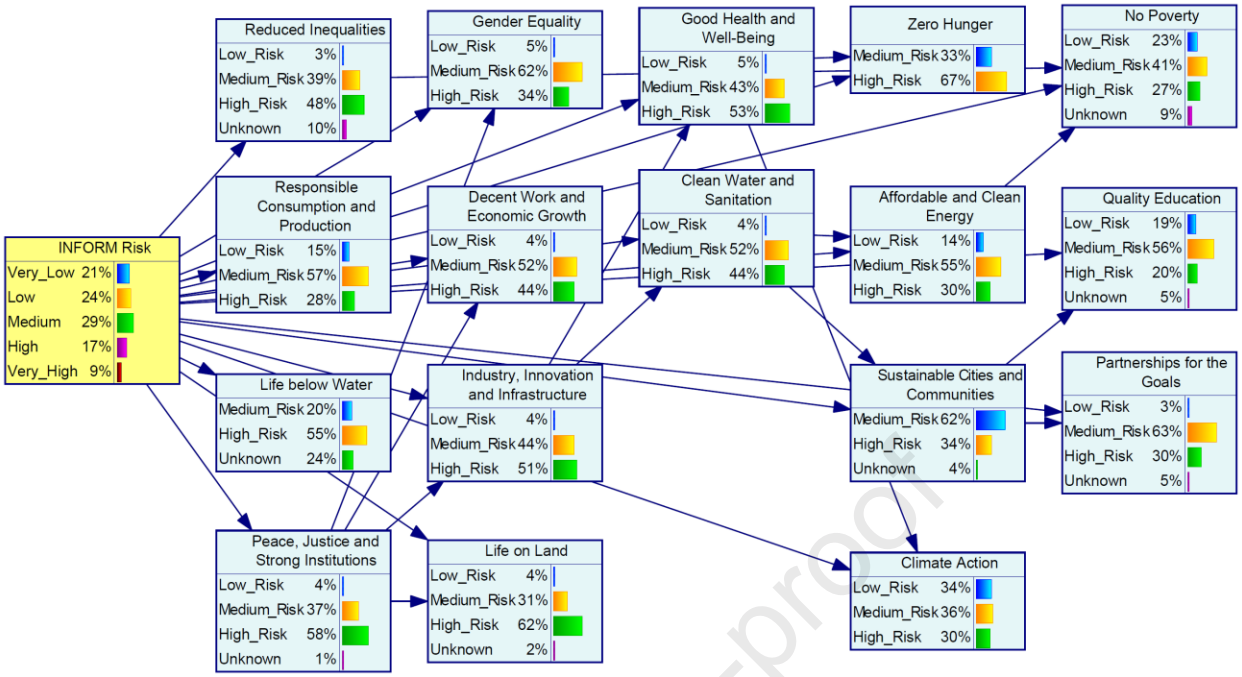
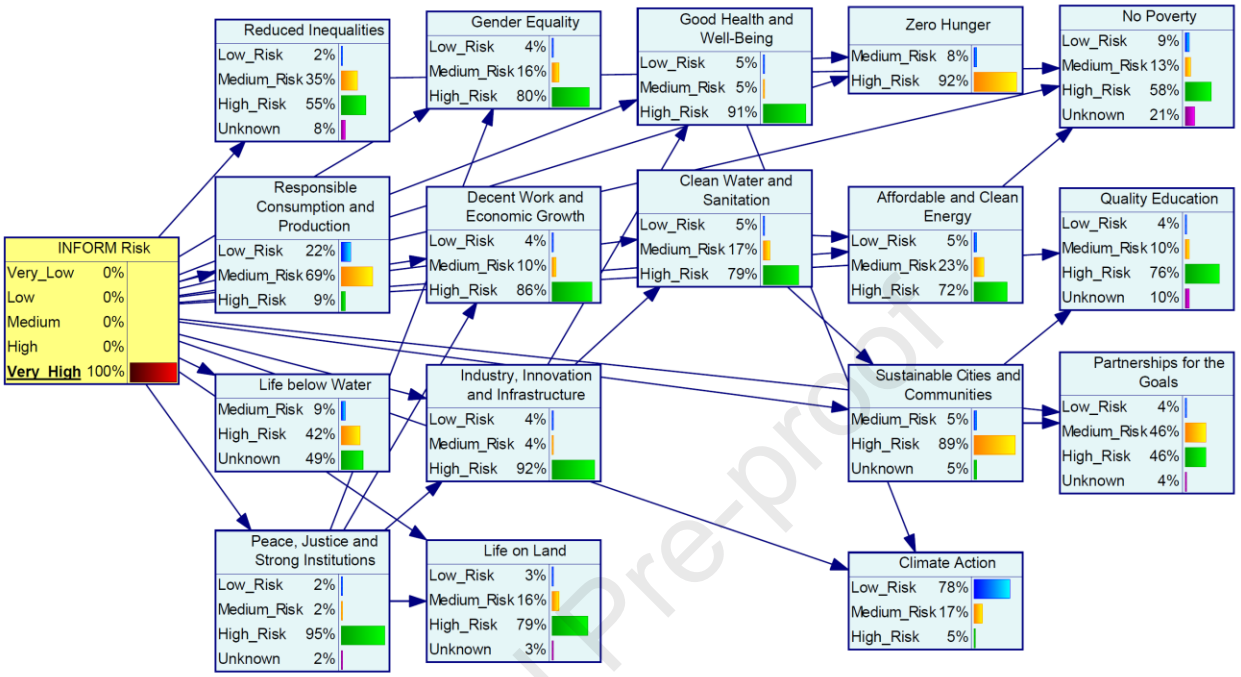


Fig. 2. A BBN model linking SDG risks to disaster (INFORM) risk.

The first BBN model developed (see Fig. 2) was analyzed for countries with a very high level of disaster risk with the results shown in Fig. 3 (a). Such countries are generally experiencing a high level of risk across many of the SDGs. They are particularly vulnerable to risks associated with 'peace, justice and strong institutions', 'zero hunger', 'good health and well-being', 'industry, innovation and infrastructure', and 'sustainable cities and communities'. Focusing on the 'high risk' category also indicates that risks associated with achieving the 'climate action' and 'responsible consumption and production' goals appear to be relatively less critical for this group of countries.

The initial BBN model developed in Fig. 2 was also analyzed for the countries with very low exposure to disaster risk (see Fig. 3 (b)). These countries are more vulnerable to the risks associated with achieving the 'climate action' and 'responsible consumption and production'

SDGs, whereas the 'no poverty', 'affordable and clean energy', and 'quality education' SDGs show a relatively low level of risk.



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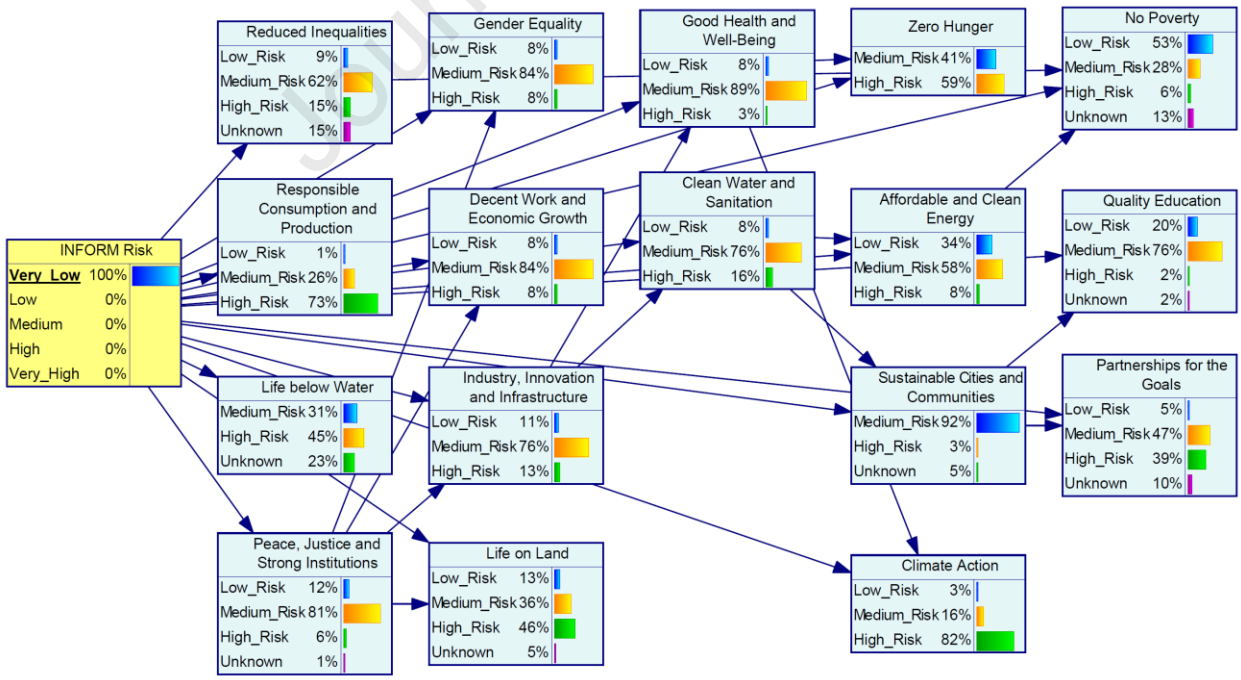


(b)

Fig. 3. A BBN model for countries with the (a) 'Very High'; and (b) 'Very Low' state of disaster (INFORM) risk.

The second BBN model represents dependencies among individual SDG risks, with COVID-19 risk representing the class variable (see Fig. 4). The bar chart associated with each SDG risk represents the probability distribution across 165 countries. Some key SDGs can be identified based on their probability of the 'high risk' state. For instance, the 'life on land' and 'zero hunger' SDGs are identified as the most critical based on the highest probabilities of the 'high risk' state. In the case of COVID-19 risk, the probability distribution is symmetrical representing an almost equal number of countries with a risk exposure above and below the 'medium' risk level. Several critical SDGs, including 'peace, justice and strong institutions', 'good health and well-being', 'sustainable cities and communities', 'industry, innovation and infrastructure', 'affordable and clean energy', 'zero hunger', 'no poverty' and 'climate action' are inter-connected across the network.

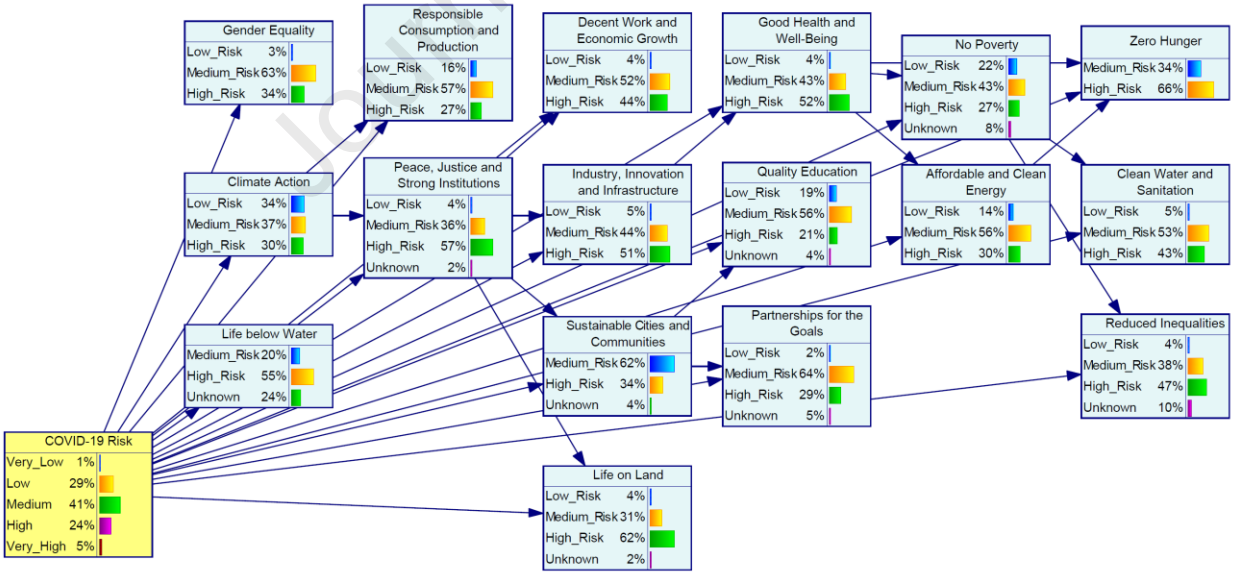
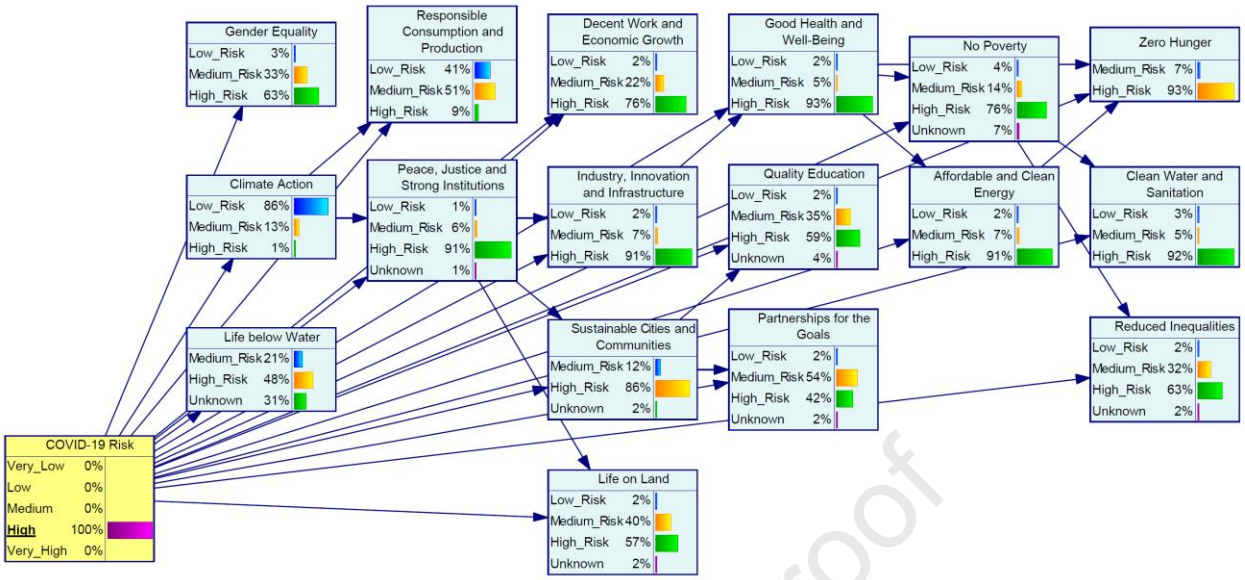


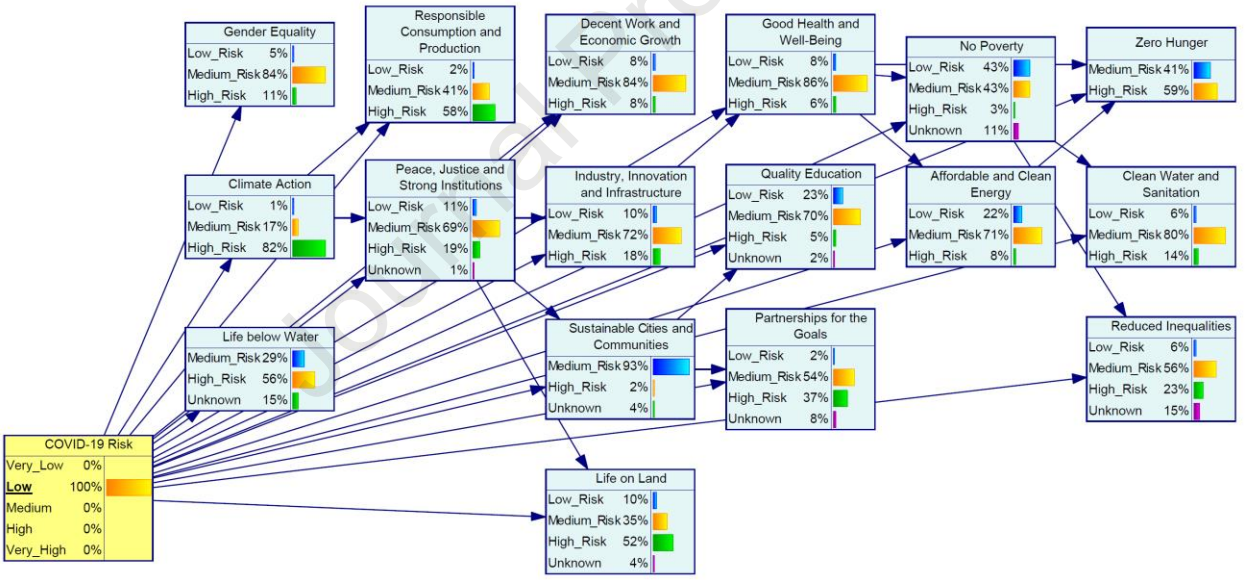
Fig. 4. A BBN model linking SDG risks to COVID-19 risk.

The second BBN model developed (see Fig. 4) was analyzed for the countries with a high level of COVID-19 risk, with the results shown in Fig. 5 (a). Such countries are more vulnerable to risks associated with achieving the 'peace, justice and strong institutions', 'zero hunger', 'good health and well-being', 'clean water and sanitation', 'affordable and clean energy' and 'industry, innovation and infrastructure' goals. On the other hand, the risk associated with achieving the 'climate action' goal is relatively much less critical. The BBN model was not analyzed for the countries with a very high level of COVID-19 risk because the sample size is too small.

The second BBN model developed in Fig. 4 was also analyzed for countries with low exposure to COVID-19 risk (see Fig. 5 (b)). These countries are more vulnerable to risks associated with the 'climate action' goal, whereas the 'no poverty', 'quality education' and 'affordable and clean energy' SDGs are associated with a relatively low level of risk. Such countries, on average, are shown to be typically exposed to a medium level of SDG-related risk. The BBN model was not analyzed for the countries with a very low level of COVID-19 risk because the sample size is too small.



(a)

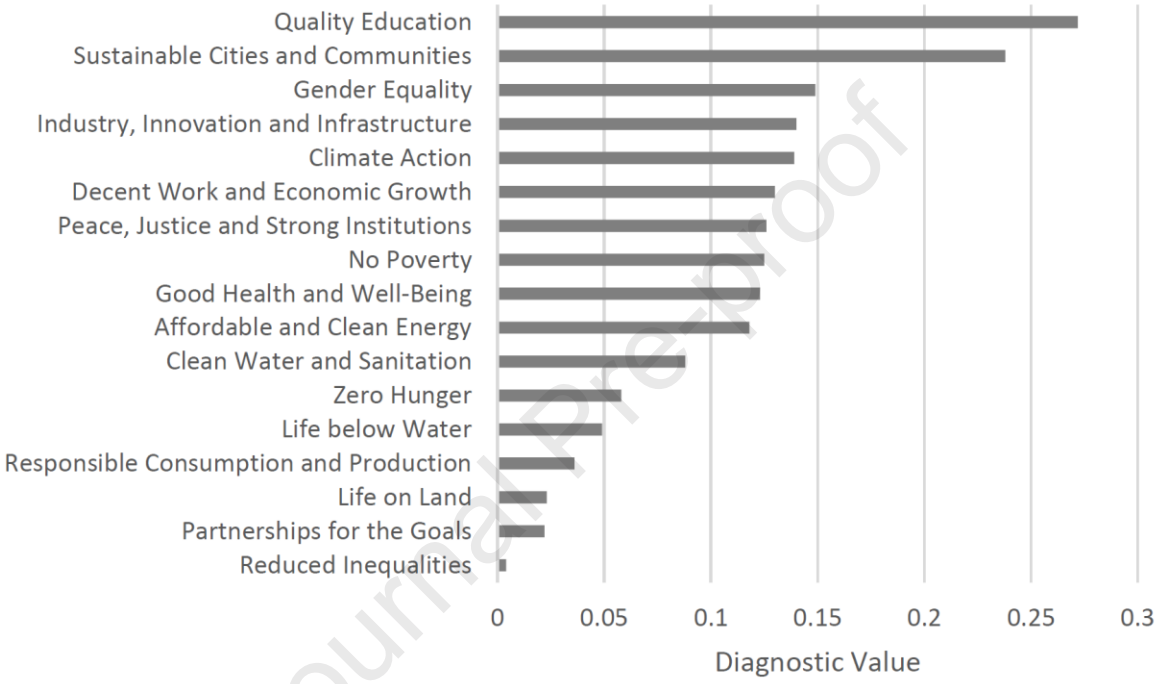


(b)

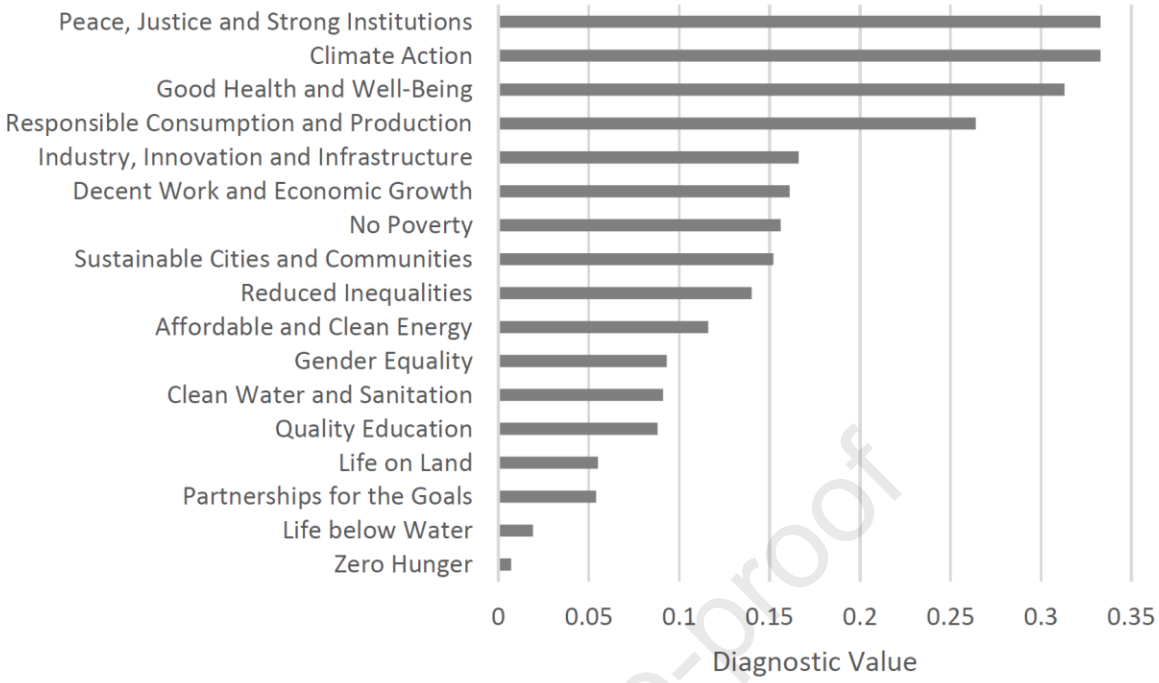
Fig. 5. A BBN model for countries with the (a) 'High'; and (b) 'Low' state of COVID-19 risk.

The SDG risks were ranked based on their predictive ability regarding the extreme states of disaster risk (see Figs. 6 (a) and (b)). This ranking is based on the assessment of the diagnostic value or cross-entropy [56], which measures the expected reduction in uncertainty of the

probability distribution of disaster risk after observing the value of individual SDGs. The 'quality education' and 'sustainable cities and communities' SDGs are the most critical in predicting the 'very high' state of disaster risk. Similarly, the 'peace, justice and strong institutions' and 'climate action' SDGs are the most critical for predicting the 'very low' state of disaster risk.



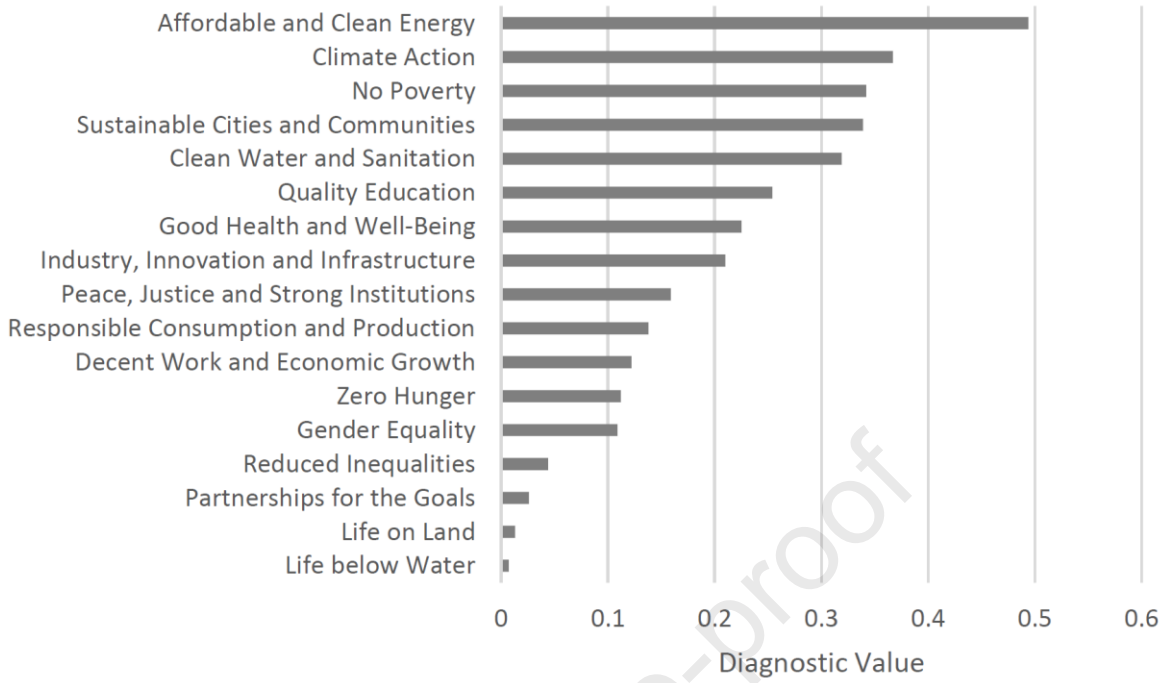
(a)



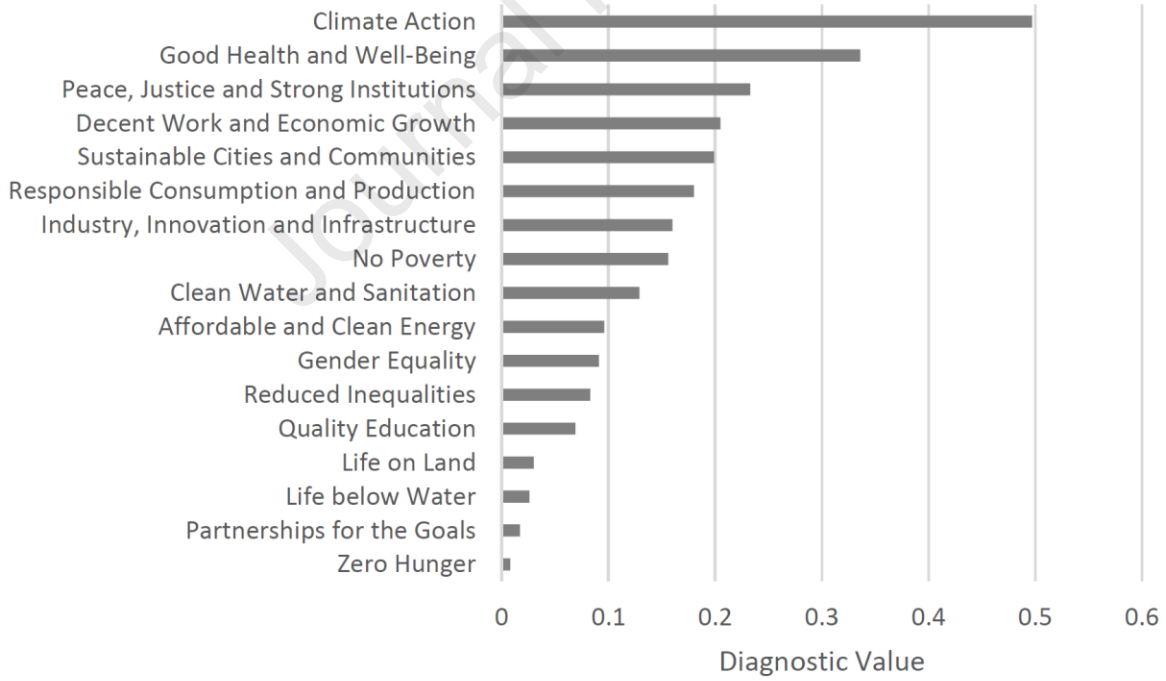
(b)

Fig. 6. Predictive ability of SDG risks for the (a) 'Very High'; and (b) 'Very Low' state of disaster risk.

The SDG risks were also ranked based on their predictive ability regarding the 'high' and 'low' states of COVID-19 risk (see Figs. 7 (a) and (b)). This ranking was based on measuring the expected reduction in uncertainty of the probability distribution of COVID-19 risk after observing the value of individual SDGs. 'Affordable and clean energy' is the most critical SDG based on its predictive ability of the 'high' state of COVID-19 risk, implying the SDG performance score could be effectively utilized to predict COVID-19 risk for the countries experiencing serious challenges associated with the pandemic. On the other hand, 'climate action' is the most critical SDG regarding its predictive ability of the 'low' state of COVID-19 risk. 'Life on land' and 'life below water' are relatively less critical SDGs for predicting either state of COVID-19 risk.



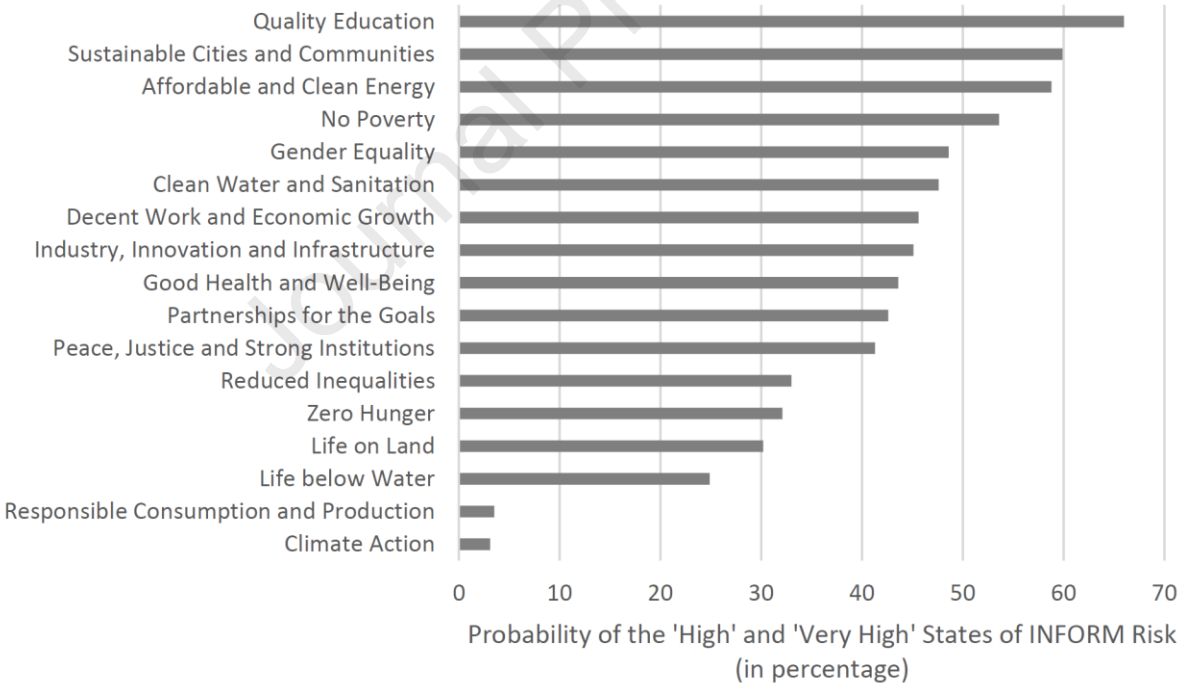
(a)



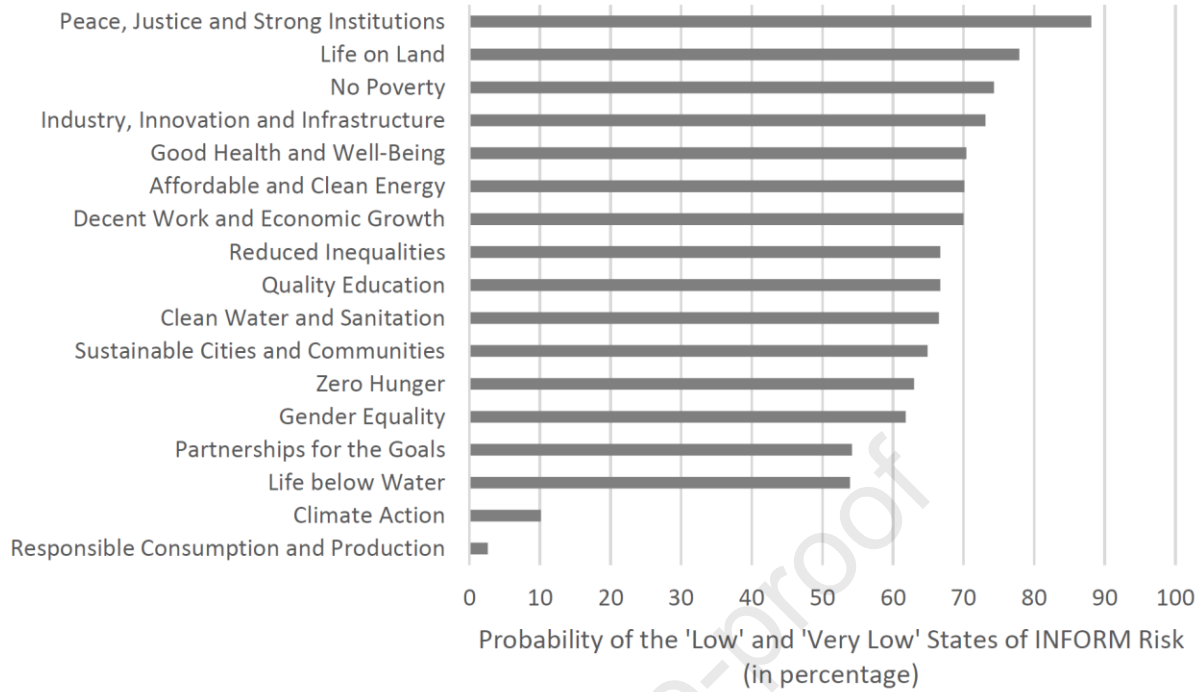
(b)

Fig. 7. Predictive ability of SDG risks for the (a) 'High'; and (b) 'Low' state of COVID-19 risk.

The impact of individual SDG risks on disaster risk was assessed for the two extreme risk states of individual SDGs. First, the vulnerability potential of each SDG risk was established based on the aggregate probability of the 'high' and 'very high' states of disaster risk corresponding to the worst-case performance scenario of the SDG risk (see Fig. 8 (a)). The 'quality education', 'sustainable cities and communities' and 'affordable and clean energy' SDGs are critical based on their vulnerability potential. Second, the resilience potential of each SDG risk was established based on the aggregate probability of the 'low' and 'very low' states of disaster risk corresponding to the best-case performance scenario of the SDG risk (see Fig. 8 (b)). 'Peace, justice and strong institutions' and 'life on land' are the most critical SDGs based on their resilience potential.



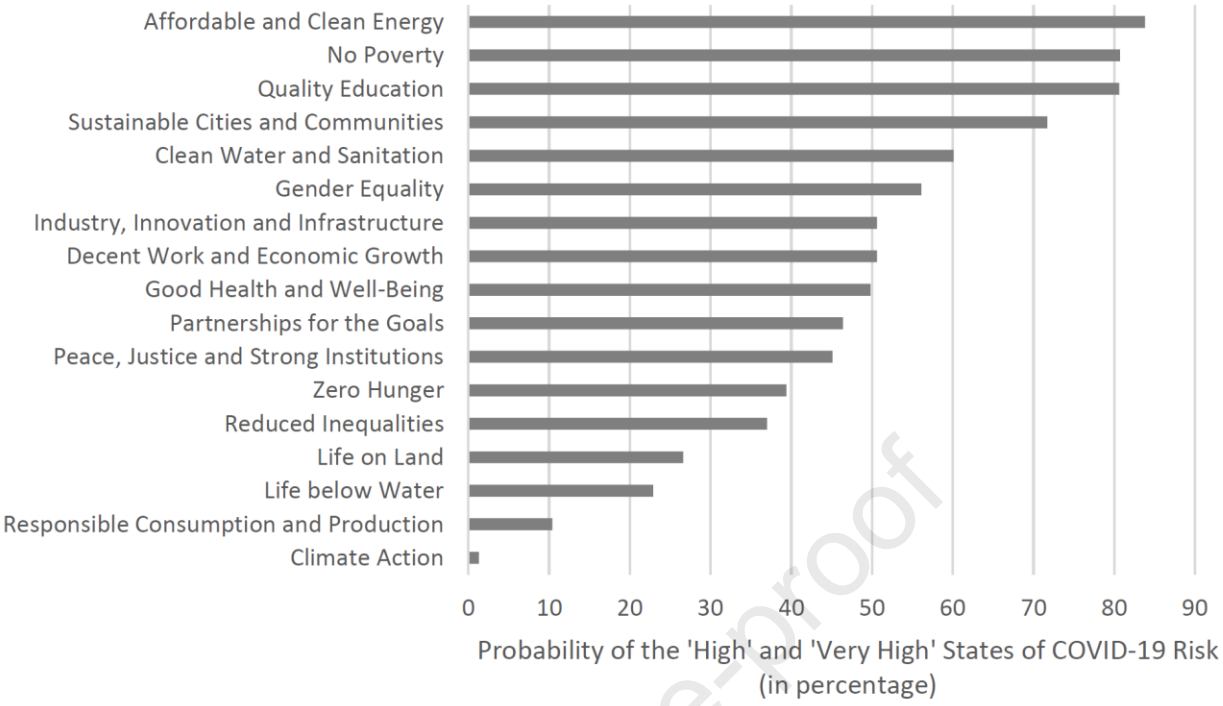
(a)



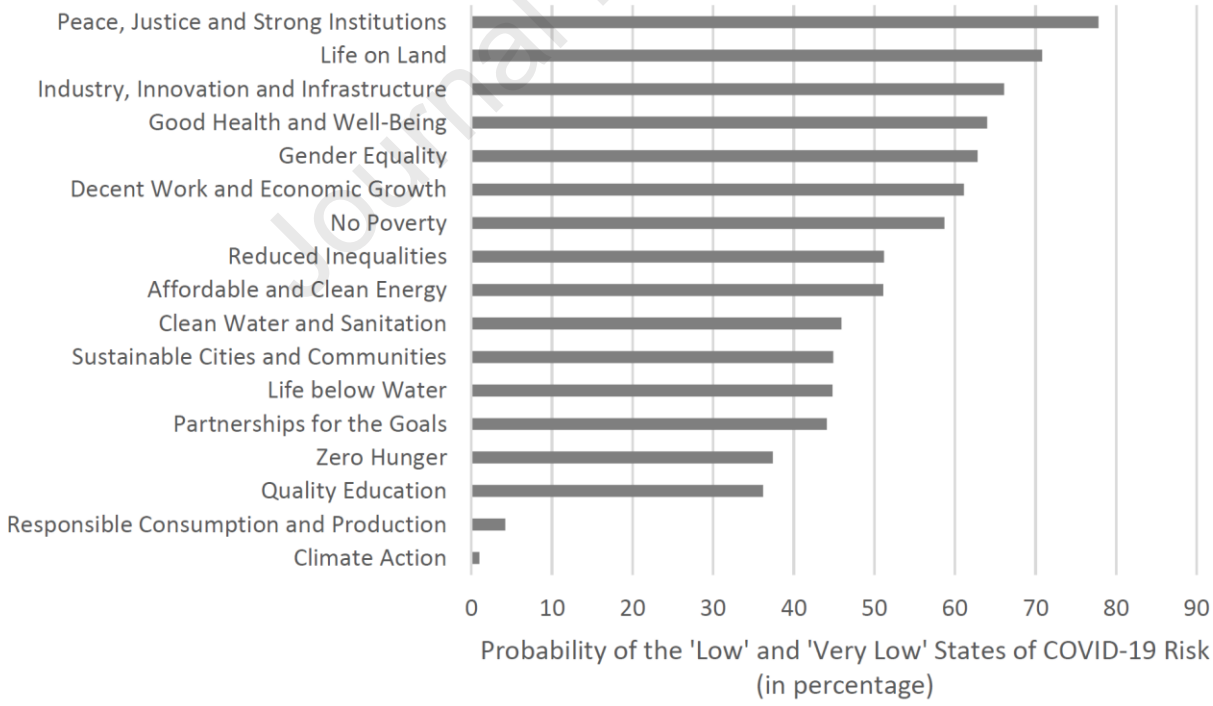
(b)

Fig. 8. Evaluation of the influence of individual SDG risks on disaster risk under two scenarios: (a) maximum vulnerability (worst-case scenario) and (b) maximum resilience (best-case scenario).

The impact of individual SDG risks on COVID-19 risk was assessed for the two extreme risk states of individual SDGs. First, the vulnerability potential of each SDG risk was established based on the aggregate probability of the 'high' and 'very high' states of COVID-19 risk corresponding to the worst-case performance scenario of the SDG risk (see Fig. 9 (a)). 'Affordable and clean energy', 'no poverty', and 'quality education' are critical SDGs based on their vulnerability potential. Second, the resilience potential of each SDG risk was established based on the aggregate probability of the 'low' and 'very low' states of COVID-19 risk corresponding to the best-case performance scenario of the SDG risk (see Fig. 9 (b)). 'Peace, justice and strong institutions' and 'life on land' remain the most critical SDGs based on their resilience potential.



(a)



(b)

Fig. 9. Evaluation of the influence of individual SDG risks on COVID-19 risk under two scenarios: (a) maximum vulnerability (worst-case scenario) and (b) maximum resilience (best-case scenario).

The four SDG risk ranking schemes shown in Figs. 8 (a), 8 (b), 9 (a), and 9 (b) were analyzed relative to their positive and negative impacts on disaster and COVID-19 risks (see Table 2). A statistically non-significant correlation was observed ($p = 0.10$) between the vulnerability- and resilience-based ranking schemes for both disaster and COVID-19 risks. However, the disaster- and COVID-19-related ranking schemes for both vulnerability- and resilience-based potential of individual SDG risks were strongly correlated ($r = 0.97\ and\ 0.82$, respectively) at a significance level of 0.001. The 'no poverty', 'quality education', 'affordable and clean energy' and 'sustainable cities and communities' SDGs are the most critical based on their vulnerability potential for both disaster and COVID-19 risks. On the other hand, the 'peace, justice and strong institutions', 'no poverty', 'good health and well-being' and 'industry, innovation and infrastructure' SDGs are the most critical based on their resilience potential for both disaster and COVID-19 risks.

Table 2. Prioritization of SDG risks based on their potential positive and negative effects on disaster and COVID-19 risks.

SDG No.	SDG	Vulnerability-based ranking regarding Disaster Risk (a)	Resilience-based ranking regarding Disaster Risk (b)	Vulnerability-based ranking regarding COVID-19 Risk (c)	Resilience-based ranking regarding COVID-19 Risk (d)
1	No Poverty	4	3	2	7
2	Zero Hunger	13	12	12	14
3	Good Health and Well-Being	9	5	9	4
4	Quality Education	1	8	3	15
5	Gender Equality	5	13	6	5
6	Clean Water and Sanitation	6	10	5	10
7	Affordable and Clean Energy	3	6	1	9
8	Decent Work and Economic Growth	7	7	7	6

SDG No.	SDG	Vulnerability-based ranking regarding Disaster Risk (a)	Resilience-based ranking regarding Disaster Risk (b)	Vulnerability-based ranking regarding COVID-19 Risk (c)	Resilience-based ranking regarding COVID-19 Risk (d)
9	Industry, Innovation and Infrastructure	8	4	7	3
10	Reduced Inequalities	12	8	13	8
11	Sustainable Cities and Communities	2	11	4	11
12	Responsible Consumption and Production	16	17	16	16
13	Climate Action	17	16	17	17
14	Life below Water	15	15	15	12
15	Life on Land	14	2	14	2
16	Peace, Justice and Strong Institutions	11	1	11	1
17	Partnerships for the Goals	10	14	10	13
		(a) and (b)	(c) and (d)	(a) and (c)	(b) and (d)
	Correlation	0.34	0.21	0.97	0.82
	p-value	0.18	0.42	0.00	0.00

5. Discussion

5.1. Summary of Key Findings

This study reveals key insights into the probabilistic relationships among SDG risks and disaster and COVID-19 vulnerabilities. The results indicate that certain SDGs, such as ‘peace, justice and strong institutions’, ‘good health and well-being’, ‘industry, innovation and infrastructure’, and ‘sustainable cities and communities’, are interconnected across both disaster and pandemic risk networks. High disaster risk is generally associated with elevated risks across multiple SDGs, while low disaster risk is linked to better performance in key SDGs, such as ‘no poverty’ and ‘sustainable cities and communities’. Similarly, high COVID-19 risk correlates with greater vulnerabilities in SDGs related to governance, health, and infrastructure, whereas low COVID-19 risk is associated with improved SDG performance in areas such as poverty reduction and energy access.

Furthermore, Table 2 highlights that SDG vulnerabilities associated with disaster and COVID-19 risks share substantial commonalities. The strong correlation observed ($r = 0.97$, $p < 0.001$) between the vulnerability-based ranking schemes for both disaster and pandemic risks suggests that countries experiencing high disaster vulnerability also tend to exhibit heightened pandemic risks. This finding supports the notion that disaster vulnerabilities are likely to be associated with pandemic vulnerabilities, reinforcing the need for integrated resilience strategies that simultaneously address both types of crises.

5.2. Implications

Policymakers can gain valuable insights through probabilistic network modeling of SDG risks in relation to specific levels of disaster or COVID-19 risk. This approach enables the prioritization of SDGs by considering the full probability distribution instead of relying solely on point estimates, a method often critiqued in risk analysis research [48, 61, 62]. Moreover, decision-makers can establish the uncertainty associated with risk-based SDG performance using such probabilistic networks. Although the models developed represent the aggregate country-level data for 165 countries, the proposed modeling approach can be adopted to develop models for individual countries representing the risk-based performance of SDGs across various states and cities. Such models can help national policymakers prioritize strategies for resource allocation.

The two network models offer valuable perspectives on the significance of specific SDG risks in forecasting the actual state of disaster or pandemic risk. Since the 17 SDGs are interdependent, their relative importance cannot be ascertained using average-based estimates, which are commonly used in practice. Rather, the 17 SDGs can only be prioritized after capturing their complex dependencies. The findings of this research indicate that the 17 SDGs hold varying levels

of importance. Specifically, certain SDGs play a more pivotal role in predicting the actual state of disaster or COVID-19 risk. Policymakers can utilize the estimates of such critical SDGs to understand the risk associated with potential disasters and pandemics.

The interdependency modeling of factors associated with disaster and COVID-19 risks has been explored in the literature [10, 48]. This study supplements the findings of related studies while establishing the association between disaster or pandemic risk and sustainability risks. For instance, Qazi *et al.* [17] reported that 'governance' is the most critical factor based on its resilience potential regarding COVID-19 risk. Similarly, this study identifies 'peace, justice and strong institutions' as the most critical SDG based on its resilience potential. Although the two variables are different, these can be mapped to some common drivers.

Cernev and Fenner [24] identified some critical SDGs based on their dependence power across interconnected SDGs, including 'peace, justice and strong institutions', 'partnership for the goals', 'no poverty', 'good health and well-being', and 'life on land'. Both network models demonstrate the relevance of these SDGs by showcasing their interconnected effects on numerous other SDGs. However, the proposed models further prioritize these SDGs while factoring in the strength of influence between interconnected SDGs.

Given the strong correlation between disaster and pandemic vulnerabilities, the SDGs can play a crucial role in holistically mitigating such systemic risks. SDG 3 (good health and well-being), SDG 9 (industry, innovation and infrastructure), and SDG 16 (peace, justice, and strong institutions) emerge as particularly significant in fostering resilience across both domains. Strengthening governance mechanisms (SDG 16), investing in healthcare infrastructure (SDG 3), and enhancing

innovation and infrastructure resilience (SDG 9) could provide dual benefits in reducing both disaster and pandemic vulnerabilities.

The 17 SDGs can be classified into the economic, social, and environmental dimensions of sustainability [41]. 'Quality education' and 'peace, justice and strong institutions' are the two most critical SDGs based on their negative and positive impact on disaster risk, which indicate the importance of the social dimension of sustainability in reducing disaster risk. On the other hand, 'affordable and clean energy' is the most critical SDG based on its vulnerability potential regarding COVID-19 risk, which represents the critical nature of the environmental dimension of sustainability in mitigating COVID-19 risk. The two BBN models developed can be split into economic, social, and environmental risk clusters and analyzed for the relative importance of each sustainability dimension. Such analyses can help policymakers split limited resources across programs related to the three dimensions of sustainability based on their relative importance.

This study presents two notable contributions to understanding the link between sustainability and disaster risk reduction. First, this study has utilized a probabilistic network to connect sustainability risks with country-level risks tied to disasters and pandemics. Second, this study has operationalized a data-driven BBN modeling approach to prioritize SDGs based on their risk-based performance regarding disaster and COVID-19 risks. While several studies have modeled dependencies among SDGs [14-16, 24, 41] and explored the connection between sustainability and disaster risk reduction [5, 22, 42], this study demonstrates a novel use of BBNs to integrate interdependency modeling of SDGs within this context.

5.3. Limitations and Future Research Directions

One limitation of the BBN framework used in this study is that it captures statistical dependencies rather than assessing causality. Future research could explore causal inference techniques to better establish directional relationships between SDG risks and disasters. Additionally, the current discretization method categorizes SDG risks into three levels: high, medium, and low. While this classification provides a straightforward way to compare risks across countries, it comes with certain drawbacks. The most significant limitation is the loss of granularity—by reducing SDG risk to only three broad categories, important variations within each category may be overlooked. For example, a country with a 90% probability of failing to achieve an SDG is grouped in the same category as one with a 70% probability, despite their different levels of risk. A five-state discretization, similar to a Likert scale, could offer a more detailed risk assessment by capturing a wider range of risk levels. Additionally, future research could explore alternative classification methods, such as percentile-based thresholds or data-driven clustering, to ensure that risk categories better reflect the actual distribution of SDG-related vulnerabilities.

Another research avenue is to examine whether high-risk countries in disaster vulnerability also experience systemic weaknesses in pandemic preparedness. Given the strong correlation observed in Table 2, further research should explore whether integrated risk management strategies—such as those proposed under the SDG framework—can enhance resilience to both disasters and pandemics.

Furthermore, this study primarily focuses on country-level risks, but disaster and pandemic risks are likely to be associated with vulnerabilities at regional or local levels. Future studies could analyze these relationships in greater detail, incorporating spatial and temporal dynamics. Lastly,

the role of the SDGs in mitigating disaster and pandemic vulnerabilities should be further explored in alignment with the broader objectives of sustainable development.

6. Conclusions

This study explored the impact of risks associated with individual SDGs on disaster and COVID-19 risks at the country level. Two BBN models were developed using three datasets to establish these dependencies. These models used network analysis to explore both direct and indirect associations among the SDGs. The 'peace, justice and strong institutions', 'good health and well-being', 'industry, innovation and infrastructure', and 'sustainable cities and communities' goals were found to influence multiple SDGs across both disaster and COVID-19 risk networks.

The findings reveal that a 'very high' state of disaster risk was associated with elevated risks across multiple SDGs, including 'peace, justice and strong institutions', 'zero hunger', 'good health and well-being' and others. In contrast, a 'very low' state of disaster risk was linked to strong performance in key SDGs such as 'no poverty', 'affordable and clean energy' and 'quality education'. For COVID-19 risk, the 'high' state was attributed to significant risk across several SDGs such as 'clean water and sanitation', 'peace, justice and strong institutions', 'zero hunger', and 'good health and well-being', whereas the 'low' state of COVID-19 risk was linked to effective risk management across SDGs such as 'no poverty', 'affordable and clean energy', and 'quality education''.

By demonstrating a strong statistical association between disaster and pandemic vulnerabilities, this study highlights the importance of holistic resilience strategies. The findings suggest that

strengthening governance, healthcare infrastructure, and infrastructure resilience can significantly reduce risks associated with both disasters and pandemics.

The study's findings offer several practical implications for policymakers. They can use the results to prioritize SDGs based on their country's level of disaster and COVID-19 risks. A causal mapping scheme, similar to the proposed models, can be adopted to prioritize risk mitigation strategies. The role of SDGs in mitigating disaster and pandemic vulnerabilities should be further explored to align risk reduction strategies with sustainable development objectives.

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Highlights

- Two BBN models are developed to explore dependencies among risks associated with SDGs and disasters/pandemics.
- Three datasets are used to calibrate and validate the models.
- A comprehensive sensitivity analysis is performed to prioritize SDGs based on their impact on disaster and COVID-19 risks.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: