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THE IMPACT OF EPIDEMICS ON GREEN INNOVATION: GLOBAL ANALYSIS

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Abstract. Epidemics and their resulting pandemics have become essential factors influencing economic development, financial stability, poverty, and ultimately a country's innovation level, including green technology innovation. This research thus investigates epidemic events' correlation to green innovation by operating with skewed panel data involving 134 countries from 1971 to 2018 and provides compelling proof that Epidemics have a detrimental effect on green innovation, not only for the current year but also for the next six years. We also show that the quality of institutions and financial development levels weaken epidemics' detrimental effects on green innovation. Overall, the findings would draw particular attention from policymakers.

Keywords: epidemics, green innovation, institutional quality, financial development.

JEL Classification: I10, O11, O31

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Introduction

Many countries around the world are experiencing resource shortages and environmental damage due to the continuous advancement of industrialization and rapid economic development. Green innovation is essential for addressing current resource shortages, environmental degradation, and other problems since it is an organic fusion of the two development ideologies of innovative and sustainable (Raihan et al., 2023). Green technology innovation forms a set of creative activities that not only meet the value needs of consumers and businesses, but also help to achieve sustainable development goals by reducing pollution and damage to the environment (Fu et al., 2023; Yin et al., 2022; Wang et al., 2023). Accordingly, numerous researches on green innovation have been undertaken in academia (Kale & Rath, 2019; Chang, 2011; Singh et al., 2020), with the goal of identifying the critical variables and potential course of action that have an impact on green innovation. Innovation in green processes and goods are at the forefront of current study into the effects of technology, policy, and market variables on green technology innovation (Li et al., 2018; Zheng et al., 2022;

Yang et al., 2022; Peng et al., 2023). However, to our limited knowledge, there are few if any studies investigating external shocks such as public health events on green innovation, thus providing the research motivation for us. We aim to fill this gap through our investigation.

Public health events represented by large-scale epidemics not only impact aggregate demand in the short term, but may also have a profound influence on the long-term development of the macroeconomy (Zeng et al., 2005; Dixon et al., 2001; Oravský et al., 2020)[1]. It is generally established that an epidemic's emergence and propagation have a negative shock to economic growth (Galbraith & Tkacz, 2013). For example, during the Spring Festival of 2020, the COVID-19 epidemic situation was spreading rapidly throughout China and dramatically reduced the demand for consumption and investment due to measures implemented to impede large-scale population movements and clusters. It also lowered service and industrial added value by impacting service industries such as tourism, transportation, catering and accommodation, and entertainment, leading to insufficient supplies as well as short-term price increases. The COVID-19 pandemic's severe socioeconomic impacts are mostly seen in rising poverty (Martin et al., 2020), mental health problems (Serafini et al., 2020)[2], and domestic abuse and criminality (Mohler et al., 2020), among others. However, up to now, there is no empirical analysis, if any, to examine how epidemics affect the degree of innovation at the national level.

Numerous studies have shown that epidemics frequently interrupt a nation's regular production order in the near term, significantly slow down social production and living, and significantly affect market entities like businesses and consumers. In the long run, epidemics can even affect the geographic distribution of the economy and future consumer preferences (Brainerd & Siegler, 2003). Epidemic-related events have a dynamic, multi-layered impact on economic expansion. Ambrus et al. (2020) investigated the impacts of cholera in London during the 19th century in the long-term and found that ten years or even a century after the outbreak of the epidemic, the difference in housing prices between the infected area and places outside of the infected area persisted and expanded, which considerably impacted the spatial distribution of poverty among residents. Therefore, it is of great importance to discuss both the long- and short-term negative influences of epidemics.

There are several reasons why epidemics is significant to green technical innovation. First, infectious disease occurrence has a severe detrimental effect on economic expansion (Dixon et al., 2001). For instance, Bloom et al. (2020) found that several global epidemics since the late 20th century have had a huge impact on economies. The human immunodeficiency virus (HIV) has caused a 3% decline in GDP per capita on the whole. During the expansion of the economy, high-quality capital and human resources can be gathered to provide a sufficient material basis with human resources being a guarantee for green innovation. Therefore, a

[1] When a significant number of individuals are affected by an infectious disease quickly, it is referred to as an epidemic. Examples include the H1N1 influenza virus, Ebola in Africa, SARS, the Black Death, and the 2019 new coronavirus (2019-nCoV). It can happen in just a certain area, or it even can be a global pandemic.

[2] According to Serafini et al. (2020), a large number of persons had a variety of psychological issues during the COVID-19 pandemic breakout and ongoing spread, including stress, anxiety, sadness, and frustration.

decline in economic growth caused by epidemics will inevitably reduce a nation's capacity for green innovation.

Second, the spread of epidemics reduces production and consumer demand, resulting in the import and export of a nation companies experiencing problems such as stagnation, default, and cancellation of foreign exhibitions, which ultimately adversely affect global import and export trade (Zhao & Deng, 2021; Wei et al., 2021). The opening up of regional trade may promote the inflow of labor-intensive and polluting industries into the region, reduce the competitiveness of relevant industries in the region, and then push out those same relevant industries, thus promoting the progress of green technology in the region. Hence, epidemics may hinder the level of green innovation since it may reduce a country's foreign trade openness.

Third, epidemics make the financial system more fragile (White et al., 2015). The damage and uncertainty caused by epidemics affect the financial system through financial markets, credit or leverage, financial institutions, liquidity, or investor expectations and further increase financial market fluctuations (Baruník & Křehlík, 2018). An efficient deployment of money, an investment strategy that is optimized, and support for increased corporate green innovation are all functions of the financial market. Thus, the prevalence of infectious diseases reduces a nation's capacity for green innovation by raising financial market uncertainty.

To summarize, the following are some ways that our research advances the body of knowledge. First, there is no other empirical study that looks at how epidemics affect green innovation. We study the impact of epidemics on green innovation using a worldwide panel dataset of 134 countries from 1971 to 2018 using the Panel Fixed Effect (FE) Poisson estimating method. We confirm that epidemics will greatly harm green innovation throughout the course of the current year, as well as the next six years. More particular, when the number of persons affected by epidemic events rises, fewer patent applications containing environmental-related technology are filed. Our investigation not only fulfills the relevant theory related to natural disaster economics[3], but also makes a great contribution for further development of innovation economics. Second, to achieve consistent results we proceed with alternative dependent and independent variables, apply different models to address any potential endogenous issues with the basic regression. The fundamental outcomes of the estimations of the impact of epidemics on green technology innovation are similar. Third, this paper explores the impacts on a variety of countries and presents evidence that the strength of institutions and the extent of financial development reduce the detrimental effects of epidemics on green innovation.

Following is the rest of this essay: In Section 1, a review of the literature is presented. Section 2 presents the empirical procedures and information. In Section 3, empirical results are given. The final section is completed.

[3] Natural disaster economics, sometimes known as "negative economics", is the study of how natural catastrophes harm the economy. In the past, studies that looked at how natural catastrophes affected economic growth were more prevalent than those that looked at how they affected technical innovation. Therefore, this paper, to a certain extent, supplements the relevant research on the economic theory of natural catastrophes.

1. Literature review

Large-scale outbreaks of epidemics throughout history have caused great pain to human society. They have severely damaged society and the economy in addition to taking the lives of hundreds of millions of people. In modern society, epidemics are occurring more frequently than famines and wars, and their economic losses to human capital and material capital cannot be underestimated. It is well known that the occurrence and spreading of epidemics have significant impacts on various aspects of the social economy, such as economic expansion, financial market (Ali et al., 2020; Yuan & Jinhua, 2022; Shahzad et al., 2022), income inequality, trade openness, labor market (Yu et al., 2020), social welfare, politics, and more (Verikios et al., 2012).

Some researchers have targeted how epidemics affect economic growth (Dixon et al., 2001; Mahal & Rao, 2005; Goel et al., 2021; Asare & Barfi, 2021; Zhang et al., 2021; Umar et al., 2021; Li et al., 2022). Alfani and Percoco (2019) investigated how the plague, which had the greatest mortality rate recorded at the time it struck in 1629–1630, influenced the growth of Italian towns. They discovered that the epidemic actually made the development of the most badly hit cities worse. Donadelli et al. (2017) showed that when epidemics have raged, news related to their diseases intervenes in investors' perceptions through news and other public media, affecting the stock market returns of pertinent pharmaceutical businesses. Ichev and Marinč (2018) also confirmed that an epidemic raises the implied volatility of the stock market by impacting investor sentiment through research on the Ebola outbreak and accompanying media coverage.

The SARS outbreak of 2003 was also a major global infectious disease outbreak that wreaked havoc on the global economy. Keogh-Brown and Smith (2008) found that it significantly reduced gross domestic product and domestic investment, but that its effects were concentrated in Hong Kong and mainland China, with less of an influence in Canada and Singapore. According to Huber et al. (2018), the Ebola virus epidemic cost the United States between US$280 million and US$32.6 billion in GDP. The estimated overall economic loss and societal burden brought on by the Ebola virus pandemic in 2014 was US$53.19 billion, of which US$18.8 billion was attributable to the high fatality rate of the epidemic in West Africa. Furthermore, some studies suggested that epidemics may negatively affect the long-term economic development (Almond, 2006; Adda, 2016; Beach et al., 2018). For example, the disease may not result in immediate death, but it will cause long-term damage to the patient's body, resulting in higher medical costs and preventing patients from participating in normal study and work, thus reducing human capital.

Except for economic growth consequences, the occurrence of epidemics has also caused damage to other aspects of the social economy (Lagoarde-Segot & Leoni, 2013; Goodell, 2020; Alon et al., 2020; Xiong et al., 2020). For example, Xiong et al. (2020) indicated that the COVID-19 outbreak caused unprecedented harm to global mental health. According to a theoretical framework established by Lagoarde-Segot and Leoni (2013), the probability of the financial sector in underdeveloped nations collapsing rises with the cumulative occurrence of big pandemics. A large portion of the group lending that banks and microfinance organizations provide to the poor is put at risk during epidemics because the aggregate shock places pressure on all members of the group (Skoufias, 2003). Owing to the HIV/AIDS pandemic, Haacker (2004) also observed a long-term shift in consumer behavior. Clearly, a global decline in home demand and consumer expenditure might pose serious difficulties for the world economy. Additionally, it is a truth that pandemics like COVID-19, which impact people from all walks of life and at different ages, do have consequences. According to Noy (2009), the risk of natural disasters is higher in developing nations. Social fractionalization, as Bjrnskov (2008) pointed out, erodes social trust. Reduced social trust results in higher transaction costs across the financial system.

The impact of infectious diseases is not always negative, as it will also produce a certain creative destruction effect (He & Harris, 2020). For example, He and Harris (2020) indicated that after the outbreak of COVID-19, many companies quickly took rescue actions to meet their social obligations. In the process of fighting the epidemic, companies actively innovated and provided goods and services in a timely manner. Some companies combined social responsibility with their own business models and business strategies to actively fulfill their social responsibilities while also enhancing their commercial value (Muhammad et al., 2020). Other researchers also obtained a similar conclusion (Khan et al., 2021; Nakada & Urban, 2020). Taking the longer view, Thomas and Rogers (2020) considered the possible advantages of promoting technological innovation in children's education.

It can be seen from the above literature that the existing empirical research mainly focuses on the social and economic consequences of epidemics, but there are several studies on the influence of epidemics on technology innovation directly. For example, there are some scholars arguing that epidemics can motivate innovation. Both Agarwal and Gaule (2022) and Sampat and Shadlen (2021) provided evidence that during the COVID-19 pandemic, government procurement encouraged biomedical innovation. In our view, it is reasonable that demand for protective equipment, medicine, and vaccines during the crisis period greatly boosted innovation in the biomedical industry within a short period, but as we will later show, the overall effect of epidemics on national innovation is negative. Data between 2019 and 2020 from Chinese A-share listed firms were reviewed by Han and Qian (2020) to determine how COVID-19 has affected innovation. They found that listed Chinese enterprises increased their R&D spending to avoid being obliterated. The only two controls included in their research were the social funding scale and quarterly regional GDP, and endogeneity was not a problem. These results may also be less compelling because they largely focused on businesses operating in the China market during the COVID-19 epidemic. The best that we can tell is that neither green innovation nor study on national effects of the impact of harsh weather on innovation. It is important to remember that technology advancement is essential to the development of human society and is an effective weapon to resolve many global challenges (Seenaiah & Rath, 2018; Bhattacharya & Rath, 2020; Rath & Bhattacharya, 2022). Due to the widespread and far-reaching effects of the COVID-19 epidemic, as well as the unprecedented opportunity for a new round of industrial reform and scientific and technological revolution, it has become the shared goal of all nations in the world to increase momentum for science and technology and use it to address issues with human development. Therefore, we fill in the literature gap through our investigation.

In comparison to previous research, the advantages of our investigation are as follows. In order to further examine the socioeconomic effects of its subdivisions, we first extend the economics of external shocks, which also adds to related study in the field of health economics. Second, the ecological economy is advanced by this article's expansion of innovation economics, which is crucial for researching green growth and sustainable development in the aftermath of epidemics.

2. Data and methodology

2.1. Data and variables

Data on green innovation are sourced from the OECD environmental statistics database and are only accessible through 2018. The Emergency Events Database provided the information on epidemics (EM-DAT). The World Development Indicators' control variable information (WDI).

Patent: The majority of academics utilized R&D spending to gauge a nation's contribution to innovation (Van Beveren & Vandenbussche, 2010). However, the following two issues cannot be avoided when using innovation input to measure innovation. First off, not all businesses have straightforward motivations for innovation, as evidenced by the presence of false research funding that prevent all R&D dollars from being applied to innovate. Second, it is impossible to determine the true efficiency of innovation because production is not always the result of investment. The underlying bias of the original data is a result of both issues. As a result, this article measures the level of innovation using the patents' innovation output metric (Zheng et al., 2020; Wen et al., 2021; Feng & Zheng, 2022). We adhere to Sun et al. (2019) in measuring green innovation by using patent applications for environmental technologies (represented by Patent). Climate change mitigation and environmental management technologies can be used to further categorize environmental-related technology.

Epidemic: As one of the extreme events, epidemics may have a significant impact of green innovation. In this paper, we consider all events of viral, bacterial, parasitic, fungal, or prion diseases declared by the WHO as epidemics (Emergency Event Database, EM-DAT). This study analyzes the epidemics variable using the entire population affected by the aforementioned pandemic episodes, following Chen et al. (2021) (represented by the epidemics variable). We suppose the occurrence of epidemics significantly negatively affects green innovation.

Research to date indicates that, in addition to diseases, other factors like as a region's population, trade openness, and economic development level affect how much green innovation occurs there.

(1) *Lnpop*: In this study, the effect of logarithmic population growth on green innovation, indicated as *Lnpop*, is controlled using the total population of each nation at the end of the year.

(2) *GDP*: In this article, the economic development level of a nation is represented by *GDP* using per capita GDP as a proxy.

(3) *FDI*: The amount of *FDI* in this study is calculated as the net inflows of FDI divided by GDP.

(4) *Openness*: Technology spillover effects, competition effects, and innovation cost reduction effects are the main influences of trade openness on green technology innovation. To measure a country's trade openness, the ratio of import and export trade to GDP is employed (proxied by *Openness*).

(5) *Education*: Human capital, as an important resource for economic and social development in the knowledge economy, motivates technological innovation through absorbing and converting knowledge into productivity. As a result, using the percentage of students enrolled in secondary schools as a proxy for human capital, we assume that it can be controlled to the greatest extent possible.

(6) *GINI*: The effect of wealth inequality on green innovation is present via an inverted U-shape trend. When it is small, increasing the income gap will promote innovation and show a price effect; but when it expands to a certain extent, increasing the income gap will reduce innovation and show a scale effect.

2.2. Data description

Figure 1 shows that there are significant fluctuations in the number of people impacted by epidemics over the course of the sample period. More specifically, the number of people affected by epidemics fluctuates greatly in the following years: 1978, 1992, 1994 and 2002. Among all the years, the population impacted by epidemics reached the maximum in 1994. The reason is that a large-scale plague broke out in India in 1994.

First, we can observe from Table 1 that the mean Patent value is 186.7424, the standard deviation of which is 838.0368, suggesting that there are significant differences in the amount of green innovation among various nations. Second, the number of individuals impacted by diseases varies considerably across nations, much like the level of green innovation in other nations. Third, *Openness*, *Education*, and *GINI* mean values are higher than their standard deviation values, suggesting that the disparities in economic growth, human capital, and income inequality between the sample countries are not as significant.

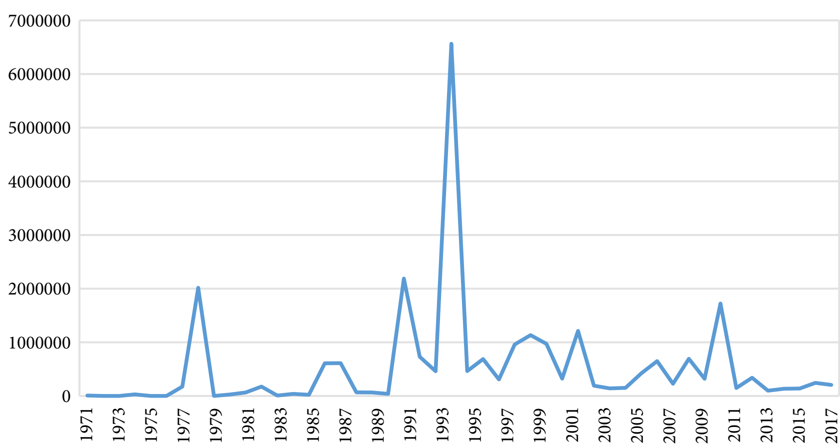

Figure 1. The evolution of the total number of people affected by epidemics from 1971 to 2018

Table 1. Data description

Variable	Observations	Mean	Std. Dev.	Min	Max
Patent	2446	186.7424	838.0368	0.14	10340.4
Epidemic	2446	0.0029	0.0476	0	2
Lnpop	2446	1.8824	1.9759	0.0226	11.1968
GDP	2446	16.4348	1.5711	11.0105	21.0253
FDI	2446	4.0590	12.2064	–58.3229	280.132
Openness	2446	78.2099	54.1938	0.1831	437.3267
Education	2446	87.9659	16.8741	5.4047	99.9949
GINI	2446	39.6326	10.6787	15.184	74.287
$GINI^2$	2446	1684.729	937.7643	230.5539	5518.559

2.3. Estimation method

This article examines the empirical effects of pandemic events on green innovation in light of the analysis above. *Patent* variable data do not follow a normal distribution, and so this paper adopts a counting model suitable for regression analysis of discrete data. The commonly used counting model is the panel Poisson regression model. Therefore, we use Poisson regression to better estimate the nexus between epidemics and green innovation (proxied by *Patent*). The Panel Poisson estimation method can reduce the impact of unobservable individual effects. Hence, we build the basic empirical research on the basis of the panel Poisson model and our benchmark model is given as follows:

$$E(Patent|Z_{it}) = \exp(\mu_0 + Epidemic_{i,t} + \gamma Z_{i,t} + \mu_i + \varepsilon_{i,t}). \quad (1)$$

$Patent_{i,t}$ denotes the *Patent* variable, representing the measure of green innovation; *Epidemic* denotes the main independent variable representing epidemic events, including viral, bacterial, parasitic, fungal, or prion diseases declared by the WHO; Z is defined as a matrix of regulating variables that may affect green technology; μ_i is defined as the constant with fixed effects of time.

3. Empirical results

3.1. Baseline estimates

Table 2 lists the empirical results of the impact of epidemic on green innovation. We only add the main independent variable *Epidemic* in the column (1), and then we add more control variables from column (2) to column (4). Column (4) contains the results of the epidemics' impact on green innovation, as well as all of the control variables. As a result, we just describe the column's findings (4). The computed *Epidemic* variable coefficient, which is –0.1839 and negative at the significant threshold of 1%, indicates that epidemics have a detrimental impact on innovation in green technology. This result is consistent with the findings of Chen et al. (2021), who came to the conclusion that natural disasters have a gravely detrimental effect on technical innovation. The possible reasons are as the follows. First, the occurrence of infectious diseases has a significant detrimental effect on economic growth. Second, the spread of epidemics reduces production and consumer demand, resulting in a country's import and export companies experiencing problems such as stagnation, default, and cancellation of foreign exhibitions, which ultimately adversely affect global import and export trade (Zhao & Deng, 2021; Wei et al., 2021). Third, epidemics make the financial system more fragile (White et al., 2015). The damage and uncertainty caused by epidemics affect the financial system through financial markets, credit or leverage, financial institutions, liquidity, or investor expectations and further increase financial market fluctuations (Baruník & Křehlík, 2018). Therefore, a decline in economic growth and trade openness and an increase of financial risk caused by epidemics will inevitably hinder a country's green innovation level.

We now look at the estimated control variable results. In this study, the coefficient of *Education* is 0.0273, which is markedly negative at the 1 percent level. This indicates that human capital is the sum of economically valuable knowledge, skills, and physical quality condensed on workers as a result of the investment. It has a crucial role in the process of economic growth and social progress, as well as in the process of green innovation and development.

Table 2. Estimation results of the Panel Poisson model

Variable	(1)	(2)	(3)	(4)
Epidemic	–0.2722***	–0.2831***	–0.2369***	–0.1839***
	(–7.94)	(–6.32)	(–3.73)	(–4.02)
GDP		–0.1582	–0.1272	–0.1269
		(–1.32)	(–0.94)	(–1.21)
Lnpop		1.8515**	1.7322**	1.6010**
		(2.42)	(2.01)	(2.25)
FDI			–0.0034	–0.0024
			(–1.61)	(–1.36)
Openness			–0.0035	–0.0033
			(–1.21)	(–1.32)
Education				0.0273***
				(2.70)
GINI				0.0046
				(0.08)
GINI^2				0.0005
				(0.53)
Country	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	2755	2576	2455	2446

Notes: The values in parentheses denote the t-statistics. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

3.2. Lagged effects of epidemics

It is believed that disasters have an evolving connection with economic development throughout time and that long-term effects are more important (Kellenberg & Mobarak, 2008). Therefore, there should be some sort of time lag when epidemics have a substantial impact on green technology innovation. Based on the analyses outlined above, this study looks into the effects of epidemics with a lag of between one and seven years on green innovation. Table 3 shows the specific outcomes. The main explanatory factors' coefficients

Table 3. Estimation results of a time lag effect of 1–7 years

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Epidemic$_{-1}$	–0.1353**						
	(–2.48)						
Epidemic$_{-2}$		–0.2242***					
		(–5.48)					
Epidemic$_{-3}$			–0.2158***				
			(–4.84)				
Epidemic$_{-4}$				–0.1518***			
				(–3.17)			
Epidemic$_{-5}$					–0.1316***		
					(–2.87)		
Epidemic$_{-6}$						–0.1182***	
						(–2.78)	
Epidemic$_{-7}$							–0.0392
							(–0.93)
GDP	–0.1249	–0.1142	–0.0832	–0.0517	–0.0205	0.0194	0.0457
	(–1.19)	(–1.08)	(–0.77)	(–0.47)	(–0.18)	(0.17)	(0.38)
Lnpop	1.7898**	1.9460***	2.0730***	2.1963***	2.2972***	2.4235***	2.5504***
	(2.44)	(2.58)	(2.67)	(2.76)	(2.79)	(2.81)	(2.85)
FDI	–0.0038*	–0.0036**	–0.0049**	–0.0071**	–0.0044*	–0.0041	–0.0013
	(–1.77)	(–2.13)	(–2.48)	(–2.52)	(–1.74)	(–1.37)	(–0.60)
Openness	–0.0024	–0.0014	–0.0007	–0.0003	0.0002	0.0008	0.0013
	(–0.98)	(–0.59)	(–0.29)	(–0.11)	(0.07)	(0.34)	(0.61)
Education	0.0231**	0.0202**	0.0185**	0.0170**	0.0144**	0.0131**	0.0116*
	(2.25)	(2.01)	(2.07)	(2.11)	(2.00)	(2.04)	(1.95)
GINI	0.0170	0.0234	0.0208	0.0164	0.0123	0.0121	0.0173
	(0.30)	(0.41)	(0.37)	(0.30)	(0.22)	(0.20)	(0.25)
GINI^2	0.0003	0.0001	0.0001	0.0001	0.0001	0.0001	–0.0000
	(0.30)	(0.16)	(0.13)	(0.14)	(0.15)	(0.08)	(–0.04)
Country	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2417	2380	2337	2297	2254	2203	2159

Notes: The values in parentheses denote the t-statistics. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. Epidemic$_{-1}$ to Epidemic$_{-7}$ represent the effects of epidemics lagging behind green innovation by 1–7 years, correspondingly.

and significance are in line with expectations from column (1) to column (6), implying that the impacts of epidemics on green innovation continue to exist in the next 1–6 years – that is, the lag effect test's regression results present that epidemics significantly stifle green innovation, which is true not only in the event year but also for the next six years. However, in column (7), the $Epidmemic_{-7}$ coefficient is not significant, demonstrating that after seven years, epidemics' detrimental effects on green innovation start to diminish. By comparing the epidemics' one-year lag coefficient to the seven-year lag coefficient, we conclude that their significant negative impact on green innovation reaches a maximum in the second year after their occurrence and gradually decreases thereafter.

3.3. Moderating effects

Some characters of one country may play a moderating effect on the relationship between epidemics and green innovation. First of all, existing research has shown that financial growth can boost the effectiveness of finance by lowering transaction costs, reducing information asymmetry, and expanding financial avenues (Sadorsky, 2011; Desbordes & Wei, 2017), thus encouraging the increase of the nation's creativity level. In addition, financial development can also increase the comparative advantages and trade scale of corresponding industries by reducing trade costs, diversifying trade risks, reducing adverse selection, and promoting a country's import and export trade (Kletzer & Bardhan, 1987). Since the occurrence of epidemics can reduce the level of green technology innovation by hindering international trade and international personnel exchanges, it can be foreseen that compared to countries with lower levels of financial development, epidemics have a smaller detrimental effect on green innovation in nations with greater financial sophistication. As a result, we create the interaction terms (represented by the formula *Epidemic * Finance*) between epidemics and financial development level. In accordance with Hsu et al. (2014), this paper measures the variable of financial development level using the total private credit issued by the banking sector to assess the proportion of GDP (proxied by Finance). The data of Finance come from the *WDI database*. The coefficient of *Epidemic * Finance* shows positive significance at the 1% level, demonstrating that epidemics have a smaller negative influence on green innovation in nations with financial development at higher levels.

Second, it is widely known that institutions contribute significantly to innovation in a nation (Mcmullen et al., 2008). Neoinstitutional economics believes that the institution is an endogenous force that maintains long-term sustained economic growth and serves as a reason for the differences in national development. As natural disasters, when epidemic events occur, if the institution in the affected nation or region is of inadequate quality, then it will further magnify the detrimental impact of natural disasters on green technology. If the institutional quality of the affected country or region is good, then it can lead to effective and organized disaster reduction and relief work and post-disaster reconstruction, minimize the loss of life and property, turn unfavorable factors into favorable factors, and promote the improvement of its level of innovation. As a result, we assume that nations with strong institutional qualities are better equipped to withstand the detrimental effects of pandemic occurrences on green innovation, whereas those with weak institutional qualities are more susceptible to external shocks.

Based on the above analysis, we generate the interaction terms between epidemics and institutional quality (proxied by *Epidemic* * *Quality*). We select the variable of regulator quality from the *World Governance Indicators* (*WGI*) *database*[4] to measure institutional quality (proxied by *Quality*). The outcomes are shown in column (2) in Table 4. We discover that the coefficient of *Epidemic* * *Quality* shows positive significance at the 5% level, indicating that good institutional quality can weaken the negative impact of epidemics on green innovation. The possible reason is that countries with higher institutional quality can speed up the progress of economic reconstruction after the occurrence of epidemics.

Table 4. Estimation results of mediating factors

Variable	Finance development (1)	Institutional quality (2)
Epidemic	–3.9815***	–0.8443*
	(–6.32)	(–1.95)
Epidemic Finance*	0.0330***	
	(6.01)	
Epidemic Quality*		0.9101**
		(2.26)
Finance	0.0008***	
	(8.42)	
Quality		–0.0506***
		(–2.91)
GDP	–0.1943***	–0.0629***
	(–18.42)	(–4.19)
Lnpop	1.3221***	1.5174***
	(24.46)	(17.68)
FDI	–0.0034***	–0.0016***
	(–5.39)	(–2.79)
Openness	–0.0012***	0.0013***
	(–3.61)	(3.24)
Education	0.0275***	0.0536***
	(23.92)	(24.37)
GINI	0.0116	–0.0216**
	(1.57)	(–2.24)
$GINI^2$	0.0003***	0.0004***
	(3.40)	(2.61)
Country	Yes	Yes
Year	Yes	Yes
N	2046	1541

Notes: Same as Table 2.

[4] Regulator quality is a reflection of the government's capacity to establish and put into action sound policies and regulations that permit and support the expanding private sector.

3.4. Robustness tests

We conduct several robustness checks to make sure that our conclusions are valid. (i) We use data when minorizing at the 1 percent and 99 percent level and when minorizing at the 2.5 percent and 97.5 percent level. (ii) We employ alternate dependent and independent variables. (iii) We employ different models. (iv) We add more possible omitted variables and apply system GMM estimation and LSDVC estimation to address the endogenous issues with the fundamental regression model.

3.4.1. Using winsorized data

In order to prevent outliers from influencing the research findings, this paper winsorizes the continuous variables at the top and bottom 1% quantiles of all the sample countries. The outcomes are displayed in column 1 of Table 5. In addition, we winsorize the continuous variables at the top and bottom 2.5% quantiles of all the sample countries. The outcomes are shown in Table 5's column (2). The coefficient of *Epidemic* is found to show negative significance at the 1% level, demonstrating that the presence of epidemics truly has a materially detrimental impact on green innovation. Consequently, the fundamental finding is solid even if we winsorize the data.

Table 5. Robustness tests: using winsorized data

Variable	when winsorizing at the 1 percent and 99 percent level (1)	when winsorizing at the 2.5 percent and 97.5 percent level (2)
Epidemic	–0.1601***	–0.0779***
	(–3.96)	(–4.44)
GDP	–0.1261	–0.1925
	(–1.25)	(–1.53)
Lnpop	2.0143**	1.8168**
	(2.51)	(2.07)
FDI	–0.0022	–0.0026
	(–1.21)	(–1.56)
Openness	–0.0003	0.0036
	(–0.13)	(1.31)
Education	0.0286**	0.0269**
	(2.53)	(2.40)
GINI	0.0074	0.0009
	(0.14)	(0.02)
GINI^2	0.0004	0.0004
	(0.50)	(0.46)
Country	Yes	Yes
Year	Yes	Yes
N	2416	2268

Notes: Same as Table 2.

3.4.2. Alternative dependent and independent variables

To begin with, we test the basic conclusion's consistency with the change in the variables' measurement using alternate independent and dependent variables. More specifically, "green innovation" refers to technical advancements that are not only beneficial to the environment but also promote sustainable growth and the climate. As a result, additional to using ecological technology patents, we also employ a wider range of ecological technology application for patents (represented by Patent1) as a proxy for measuring green innovation. This category includes a sustainable ocean economy, climate change adaptation technologies, and environment-related technologies. The OECD environmental statistics database provided the information on total patent applications.

Table 6's column (1) in column (1) displays the results. We discover that the significant detrimental effect of pandemic occurrences on green innovation still exists when the dependent variable is *Patent1*. In addition, when it comes to the independent variable, we also choose the number of deaths according to Chen et al. (2021) brought on by epidemics (represented

Table 6. Robustness tests: alternative variables and estimation strategy

Variable	*Patent1* as dependent variable (1)	*Epidemic1* as independent variable (2)	Fixed effect model (3)	Interactive fixed Effect model (4)	Panel Tobit model (5)
Epidemic	–0.0711***		–1.1910***	–1.3389***	–1.1910***
	(–11.62)		(–3.75)	(–3.65)	(–5.92)
Epidemic1		–0.0002***			
		(–6.41)			
GDP	0.0192***	–0.1154***	0.7937	0.4250*	0.7937***
	(9.60)	(–13.07)	(0.89)	(1.86)	(3.22)
Lnpop	2.5421***	1.5501***	–0.8287*	–2.8467	–828.6550***
	(258.27)	(35.17)	(–1.69)	(–1.36)	(–7.99)
FDI	–0.0013***	–0.0025***	–1.8360	–0.0932	–1.8360**
	(–10.55)	(–4.57)	(–1.40)	(–0.75)	(–1.99)
Openness	–0.0007***	–0.0036***	–2.6734	–0.0182	–2.6734***
	(–12.38)	(–15.68)	(–0.92)	(–0.33)	(–3.91)
Education	0.0268***	0.0273***	–3.3768	0.4390***	–3.3768***
	(132.91)	(27.67)	(–1.65)	(3.91)	(–3.12)
GINI	–0.0810***	0.0087	34.5293	0.0270	34.5293**
	(–59.31)	(1.37)	(0.71)	(0.02)	(2.35)
$GINI^2$	0.0014***	0.0004***	–0.1780	0.0031	–0.1780
	(69.16)	(4.63)	(–0.44)	(0.23)	(–1.03)
Country	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	4112	2446	2456	2456	2456

Notes: Same as Table 2.

by Epidemic1) to assess the intensity of epidemics in addition to the number of persons impacted by epidemics. The results appear in column (2) in Table 6. The coefficient of *Epidemic1* is found to be significantly negative at the 1% level, demonstrating that the presence of epidemics does have a materially detrimental impact on green technology innovation. The quantity of environmental technology patent applications falls as the quantity of epidemic-related mortality rises. Therefore, even if we alter several independent and dependent factors, the primary conclusion remains valid.

3.4.3. Alternative estimation techniques

In the basic regression, to discuss the effect of epidemics on green innovation, we employ a panel Poisson model. In the following section, this paper fixes country and year variables while using a fixed-effect panel model to examine the link between epidemics and environmentally friendly innovation. Table 6 column (3) lists the results. We observe from the findings that the coefficient of Epidemic is likewise negative at the significant level of 1%, demonstrating that the results are still robust with the basic regression results when we apply the panel fixed effect model. Additionally, the interactive fixed effects model in a panel can show more accurate reflection on reality than the classic panel fixed-effects model in terms of specific problems. Additionally, it can adequately describe the variety of responses people have to these shocks as well as multidimensional shocks in the actual economy (Bai, 2009). As a result, we employ the fixed-effect panel interactive model. to retest the fundamental regression findings.

Table 6 shows the results in column (4), where we see that they agree with the key findings. The Tobit model for panel data is also used to assess the connection between disease and green innovation, because the dependent variable is left-censored at 0, and the findings are presented in column (5) of Table 6. Based on the foregoing findings, we may conclude that epidemics have a large negative influence on green innovation that is consistent across estimate models.

3.4.4. Endogeneity concerns

Rationality analysis for the results of epidemics on green innovation may have endogenous problems mainly caused by omitted variable errors regarding issues with reverse causality (Afesorgbor, 2019; Acemoglu et al., 2019). The bias in empirical analysis caused by omitted variables can be greatly decreased by tightly regulating other variables that affect a nation's green innovation. To start, we incorporate Fariss's (2014) latent score, which evaluates the degree of repression and adherence to rights to physical integrity (proxied by *Human*). In column (1) of Table 7, the outcomes of regulating the *Human* variable based on the fundamental regression are displayed.

Second, the process of urbanization brings about the agglomeration of human capital and educational resources, which are beneficial in support of the growth of green technology innovation. Therefore, the amount of urbanization and its influence on green innovation is measured in this paper using the ratio of urban to total population in each country, which is recorded as *Urban*. The empirical results after controlling *Urban* are in column (2) in Table 7.

Table 7. Robustness tests: adding more control variables

Variable	(1)	(2)	(3)	(4)
Epidemic	–0.2040***	–0.1916***	–0.1971***	–0.8082**
	(–3.67)	(–3.49)	(–3.66)	(–2.11)
GDP	–0.1285	–0.1066	–0.1398	–0.1844*
	(–1.04)	(–0.95)	(–1.14)	(–1.86)
Lnpop	1.7426**	1.8763**	1.6193**	1.7413**
	(2.09)	(2.19)	(2.20)	(2.24)
FDI	–0.0044**	–0.0048**	–0.0054**	–0.0013
	(–1.97)	(–2.27)	(–2.53)	(–1.10)
Openness	0.0003	0.0008	–0.0015	–0.0010
	(0.11)	(0.26)	(–0.56)	(–0.52)
Education	0.0273**	0.0277**	0.0273*	0.0543***
	(2.04)	(2.02)	(1.84)	(3.54)
GINI	0.0242	0.0253	0.0373	–0.0697
	(0.42)	(0.45)	(0.76)	(–0.96)
GINI^2	0.0002	0.0002	0.0001	0.0009
	(0.24)	(0.23)	(0.09)	(0.90)
Human	–0.0913*	–0.0703	–0.0894	0.0040
	(–1.88)	(–1.09)	(–1.34)	(0.05)
Urban		0.0065	0.0135	–0.0062
		(0.81)	(1.46)	(–0.60)
Consumption			–0.0156	–0.0110
			(–1.40)	(–1.12)
R&D				0.0442
				(0.66)
Country	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	2755	2576	2455	2446

Notes: Same as Table 2.

Third, many academics have studied that size of government is non-linear correlated to economic expansion, such as Herath (2012) and Asimakopoulos and Karavias (2016). Furthermore, it is well known that technical innovation is the source and power engine of economic growth, and therefore, the level of innovation will always fluctuate depending on the size of the government. Thus, we control over the effect of government size and use GDP divided by final consumer expenditure to calculate the size of the government (proxied by *Consumption*). The empirical results after controlling *Consumption* are in column (3) in Table 7.

Fourth, effects of R&D on innovative activities have been documented in the empirical literature (Ho et al., 2018; Hsu et al., 2014). More expenditure leads to more creativity and further discovery. Following a similar method applied by Marino et al. (2016), we employ the GDP to R&D spending ratio (proxied by *R&D*) to control the input intensity to green innovation. The results are given in column (4) in Table 7. We see that after controlling the above three potential missing variables, epidemics continue to have a negative impact on green innovation, which once further demonstrates how solid the results of this research are.

In this research, using GMM, the harmful effects of extreme weather events on green innovation are re-estimated in order to account for the dynamic trend and the endogenous issue. It is important to note that the system GMM estimator is better suited to overcoming weak instrumental elements' influence and restricted sample bias than difference GMM (Bond et al., 2001). As a result, we solely employ system GMM to verify the fundamental regression's reliability. The outcomes are shown in Table 8's column (1).

Table 8. Robustness tests: system GMM and LSDVC estimators

Variable	System GMM (1)	LSDVC (2)
L.Patent	0.9705***	1.0067***
	(39.35)	(309.09)
Epidemic	–1.0386***	–1.0629***
	(–2.93)	(–3.37)
GDP	1.8407	0.4189
	(0.19)	(0.12)
Lnpop	85.5117	9.1149
	(1.25)	(0.40)
FDI	0.2487	0.0015
	(0.91)	(0.00)
Openness	0.6679	–0.0736
	(0.89)	(–0.47)
Education	2.5870	–0.0023
	(1.05)	(–0.01)
GINI	11.5787	2.1038
	(0.39)	(0.51)
$GINI^2$	–0.1786	–0.0169
	(–0.48)	(–0.30)
Country	Yes	Yes
Year	Yes	Yes
AR (1)-*P*	0.095	
AR (2)-*P*	0.315	
Hasen-P	0.645	
N	2060	2060

Notes: Same as Table 2.

In order to verify the accuracy of the instrumental variables and the second-order correlation of the residual sequence, this estimation approach necessitates a test for overidentification and a test for sequence correlation. The model regression's applicability is demonstrated by the P values of the AR (2) and Hansen tests. In addition, from the coefficient of the *Epidemic* variable, this article provides compelling proof that epidemics and green innovation are significantly related to one another. In other words, in keeping with the main finding, epidemics have severely decreased a nation's degree of green innovation.

In comparison to the usual Least-Squares Dummy Variables estimator, although they are asymptotically consistent, the dynamic GMM estimators used here have a significant variance for small samples. The SYS-GMM estimate could also result in a weak instrumental variable issue and estimation bias in the case of a limited sample size. Kiviet (1995) introduced a bias-corrected Least-Squares Dummy Variables (LSDVC) estimator that ensures the estimation results are unbiased and consistent. We estimate the LSDVC models to assure the robustness of our results. The outcomes of the LSDVC model are given in column (2) in Table 8. As indicated in this column, the coefficient of the *Epidemic* variable is in line with the fundamental regression. Hence, after considering and dealing with the possible endogenous problems, the adverse effect of epidemics and green innovation still exists.

Conclusions and policy implications

As a special natural disaster, an epidemic brings great challenges to global economic development. Based on this, this article first examines the impact of epidemics on environmental innovation. It documents strong evidence that epidemics can greatly impede green innovation's emergence. More particular, when the quantity of persons affected by epidemic events rises, fewer patent applications containing environmental-related technology are filed, which not only exists in a current year of an epidemic, but also for the following 6 years. Additionally, the bad effects of epidemic events are more pronounced in nations with poor financial development and institutional quality levels, suggesting that a nation's financial and institutional quality can mitigate the negative effects of epidemics on green innovation. By illustrating how epidemics affect the development of green technologies, this article advances relevant work in the environmental and innovation domains as well as the field of health economics and further deepens the effects of public health crises. In addition, our investigation also fulfills the relevant theory related to natural disaster economics, which is a "negative economics". Therefore, the following policy ramifications are presented for nations that are more susceptible to epidemic occurrences.

First, because pandemic catastrophes are a common sort of abrupt natural event, every government must integrate emergency management into its routine activities rather than seeing it as a one-time emergency duty. Second, this paper discovers that the improvement of financial development can weaken the adverse influence of epidemics on green innovation. Therefore, the government should strengthen the financial coordination and supervisory mechanism to minimize systemic financial risks and to ensure the safety and stability of the financial market. Last but not least, a sound institutional environment can compensate in a certain sense for the negative effect of epidemics on a country's green innovation. Therefore, in order to better cope with external shocks, the government should improve its institutional construction and create a more democratic, efficient, stable, and excellent institutional environment. The propagation of any virus is not constrained by national boundaries; thus all countries should collaborate to stop the occurrence of infectious diseases and fend off their harmful effects. Especially as the level of economic globalization is increasing, the global supply chain is getting strained, and the transnational spread of infectious diseases is more likely to occur, governments of all countries should unite to prevent the occurrence of infectious diseases and combat their negative effects. With regard to future research, this paper suggests to further investigate the influence of epidemics on short-term and long-term technological innovation in various industries.

In terms of potential directions for future research, this report advises examining the following facets. First, we can further subdivide green innovation into energy related innovation, water innovation, climate related innovation, etc. and further analyze the impact of epidemics on the subdivision of green technology innovation. Additionally, we can explore how COVID-19 affects green innovation by using more frequent data, such as daily data or monthly data. Furthermore, we can explore how to promote green innovation level or increase sustainable development in the post-epidemic era.

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