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REVIEW

COVID-19 Pandemic Risk Assessment: Systematic Review

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Background: The COVID-19 pandemic presents the possibility of future large-scale infectious disease outbreaks. In response, we conducted a systematic review of COVID-19 pandemic risk assessment to provide insights into countries' pandemic surveillance and preparedness for potential pandemic events in the post-COVID-19 era.

Objective: We aim to systematically identify relevant articles and synthesize pandemic risk assessment findings to facilitate government officials and public health experts in crisis planning.

Methods: This study followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines and included over 620,000 records from the World Health Organization COVID-19 Research Database. Articles related to pandemic risk assessment were identified based on a set of inclusion and exclusion criteria. Relevant articles were characterized based on study location, variable types, data-visualization techniques, research objectives, and methodologies. Findings were presented using tables and charts.

Results: Sixty-two articles satisfying both the inclusion and exclusion criteria were identified. Among the articles, 32.3% focused on local areas, while another 32.3% had a global coverage. Epidemic data were the most commonly used variables (74.2% of articles), with over half of them (51.6%) employing two or more variable types. The research objectives covered various aspects of the COVID-19 pandemic, with risk exposure assessment and identification of risk factors being the most common theme (35.5%). No dominant research methodology for risk assessment emerged from these articles.

Conclusion: Our synthesized findings support proactive planning and development of prevention and control measures in anticipation of future public health threats.

Keywords: meta-analysis, coronavirus, pandemic risk management, WHO COVID-19 research database, data visualization

Introduction

The outbreak in 2019 of the novel coronavirus disease (COVID-19), which the World Health Organization (WHO) officially declared a global pandemic on 11 March 2020,[1] is currently the most detrimental worldwide public health event of the twenty-first century. The disease's rapid transmission not only has imposed tremendous pressures on the public health systems, but it also has severely disrupted the financial markets,[2,3] our society and the global economy,[4] and our environment.[5] Furthermore, this threatening pandemic caused drastic harms to people's mental health. People affected by COVID-19 showed relatively higher rates of adverse psychiatric outcomes like anxiety, depression, stress, and psychological distress.[6] Another gloomy impact of COVID-19 to the society was that misinformation and fake news about transmission, prevention, and medical treatment[7,8] were spread within and across online communities broadly and swiftly, causing the prevalence of incorrect knowledge about COVID-19. These wide-scale deadly effects made research works relating to COVID-19 pandemic risk assessment so important that governments, public health professionals, and scientists could gain insights from research findings for disease prevention and control strategies.

Since its first appearance, COVID-19 has been a hot topic of research in many fields, and especially in health-related disciplines. Even now, the research enthusiasm for COVID-19 has not abated, because the virus has continued to

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transform itself into new variants[9] and has caused successive waves of large-scale transmission with exponential increases in new infections globally for the past 3 years.

As we have stepped into the post-COVID-19 era, enormous volumes of extant research studies on the various aspects of the COVID-19 pandemic have been published. During COVID-19 pandemic, people often used online social media platform to search for information on recent development, communicate their views, and express their feelings. The analysis conducted by Chandrasekaran et al[10] on COVID-19–related tweets from Twitter data indicated that the contents could be broadly classified into 10 different themes. Four commonly concerned themes were spread and growth (15.45%), treatment and recovery (13.14%), impact on the health-care sector (11.40%), and government response to the pandemic (11.19%). In light of the above observations, it is noteworthy to work out some statistics describing the coverage distribution of the current COVID-19 pandemic risk assessments such that their diversity and applicability could be demonstrated to the concerned parties for acquiring a more comprehensive and detailed understanding on how to prevent, manage, treat, and address the issues. Nevertheless, staying vigilant to the spread of infectious disease and getting more well prepared are essential. Thus, the objectives of our study were to provide a systematic review of the COVID-19 pandemic risk assessment.

The articles in this review were selected from the World Health Organization (WHO) COVID-19 Research Database,[11] which is a centralized database that pools publications from different health-care research databases such as Ovid, PubMed, Scopus, Web of Science, and others. At the time that we searched the articles, there were already more than 620,000 records, and the size of the pool is continually growing because it is updated weekly and new publications are added regularly. The WHO was recognized for its outstanding work in building the COVID-19 Research Database and for the excellence of its content.[12] The relevant articles were characterized using the following six research questions (RQs).

RQ1: Study Location

RQ2: Types of Variables Used

RQ3: Availability of the Materials Used to Generate Research Outcomes

RQ4: Use of Data-Visualization Techniques

RQ5: Research Objectives

RQ6: Research Methodologies

This paper is subsequently organized as follows: In the Methods section, we describe thoroughly how the final eligible list of articles was selected in order to provide the best possible answers to our research questions. In the Results section, we develop our classification framework for the research questions and present the summary statistics of the eligible articles, with the aid of tables and charts. In the Discussion section, we provide our key findings, along with some recommendations for policymakers and health-care experts and researchers to deal with the potential for any future outbreak of disease. Finally, the Conclusions section gives a brief recap of the key conclusions that can be drawn from our findings.

By synthesizing insightful findings with the help of tables and charts, this study aids policymakers, health-care experts, and researchers in creating preparedness and surveillance efforts for possible new waves of COVID-19 and/or the emergence of new infectious diseases in the future.

Methods

Overview and Selection Process

We conducted a systematic review of literature reviews on COVID-19 pandemic risk assessment sourced from the World Health Organization (WHO) databases, according to the Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) guidelines.[13] Two researchers worked independently to select the final eligible articles in this review. First, one of them used the electronic search engine available in the WHO database to generate a list of potentially eligible articles. Next, each article in the potentially eligible list was retrieved either directly from the WHO database or from the journal website on which that article was published. Finally, the other researcher manually screened each article to ensure that those in the final eligible list satisfied our inclusion criteria and did not meet our exclusion criteria. All disagreements between the two researchers over the eligibility of particular articles were resolved through discussion with a third researcher.

Information Source and Search Strategy

We identified the relevant articles for this review by searching the World Health Organization (WHO) COVID-19 Research Database from its inception to 12 July 2022. This electronic database is freely and publicly accessible online. It searches, on a frequent basis, a vast number of popular databases to obtain current articles reporting global research on the coronavirus disease (COVID-19). During the time that we were searching the articles, the three largest sources of articles, in terms of the quantity in the WHO COVID-19 Research Database, were MEDLINE, Scopus, and Web of Science.

The search strategy was straightforward, because nearly all articles in the WHO COVID-19 Research Database are within the domain of the COVID-19 pandemic. No filters or limits were placed in the first screening process – we just screened out articles that lacked a title, name, or abstract, and then we removed duplicate records. Approximately 56% of the records remained and moved forward to the next screening process.

Eligibility Criteria

In our criteria, we included articles that related to one of three main scopes of study: (1) COVID-19, using the keywords "COVID" or "Coronavirus disease 2019", (2) pandemic risk, using the keywords "pandemic risk", and (3) risk assessment, using the keywords "risk assessment."

The language of each article, the nature of the article, the research field of study, and the accessibility of each article was the four filters in our exclusion criteria. We excluded (1) non-English-language articles, (2) articles with a nature equivalent to letters/comments/abstracts, and (3) fields of study belonging to "clinical", "medical", "virology", "finance", "business", "logistics", "supply chain", and "pharmacy". For criterion (4), the accessibility of the article, inaccessible or nonidentifiable articles, including non-open-access papers, full-text pdfs, unavailable papers, and papers without a valid DOI (Digital Object Identifier) were excluded because we could not examine the entire papers to determine whether they were within our research focus.

After the screening, we conducted an additional manual scan of the eligible articles. Meta-analyses and articles not relating to our research questions were then excluded, leaving a final eligible list of 62 articles. A description of the inclusion and exclusion criteria of the articles for this study is presented in Table 1. The quality of the included articles was assessed using the Effective Public Health Practice Project (EPHPP) Quality Assessment Tool.[14] Each included article was assessed by two reviewers, who conducted the assessment independently.

Results

The article search and selection process is shown in Figure 1. Initially, there were 626,900 records in the WHO COVID-19 Research Database. Only 410 records were entered into our "Eligibility" phase. In the last phase, "Included", the number of records was further reduced to 62. These 62 articles were identified as the final candidates for analysis in this review.

Table 1 Summary of the Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Article type	Topic relevant to COVID-19, pandemic risk or risk assessment	Letters, comments, abstracts, non-journal, systematic review and meta-analysis
Field of study	Any field except those fields in the Exclusion column	Clinical, medical, virology, finance, business, logistic, supply chain and pharmacy
Language	English language	All other non-English language
Accessibility	Open access	Article with non-valid DOI or no full text pdf available

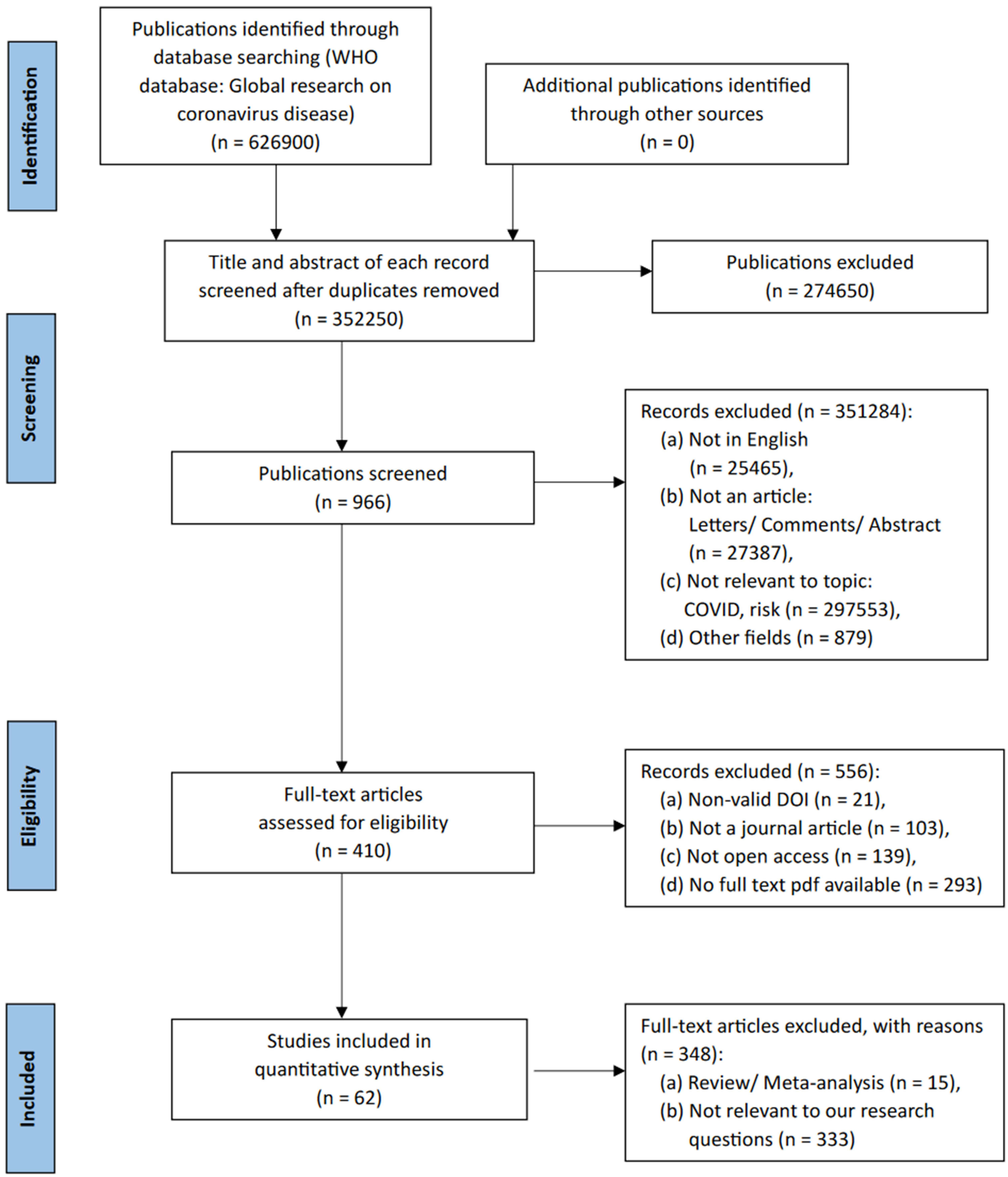


Figure 1 PRISMA flow diagram of the article selection process.

We developed our classification framework based on six research questions. After the classification framework was developed, one of the reviewers performed a preliminary allocation by assigning each of the 62 included articles according to the respective classification types from each research question. To mitigate the risk of bias, another reviewer validated the preliminary allocation by assessing the individual classification of each article in each research question.

Finally, a third reviewer examined all of the classification discrepancies between the first two reviewers and arrived at the final summary statistics for the six research questions, which we then described and visualized in the tables and figures shown below.

RQ1: Study Location

We divided the articles into four different sizes of the geographical areas in which the COVID-19 pandemic risk was assessed: regional areas, specific areas, local areas, and global coverage. The study location of one article was not classifiable because that article was a pandemic risk modelling evaluation and no location was indicated. Descriptions of the four sizes of geographical areas, with some examples, are given in Table 2.

Approximately one-third (32.3%) of the articles had conducted COVID-19 pandemic risk assessment in a local area, and another one-third had assessed the risk globally. Regional areas had attracted the least attention of researchers, constituting just 6.5% of the 62 included articles (Figure 2).

Among the 17 articles concerned with risk assessment in specific areas, five articles focused on a single province in China, such as Qingdao[17] and Hubei.[18] India followed China as the second most popular specific area to have been studied, but the frequency was just two. The remaining 10 specific areas were each at a different location (Figure 2).

Regarding the 20 local-area articles, the countries of interest were quite diverse, with 12 different countries, only two of which had been studied in more than two articles. China (seven articles) was again the top country to arouse interest and to have been studied in a countrywide risk assessment, followed by the USA (three articles).

RQ2: Types of Variables Used

We classified the nature of the variables used in the included articles into six different types of data that the variables represented: (1) epidemic data, (2) population/demographic data, (3) mobility/transportation data, (4) socioeconomic data, (5) survey data, and (6) environmental data. Table 3 gives examples of each data type.

Table 2 Description of the Four Sizes of Geographical Areas

Geographical Area	Description	Example Geographical Coverage
Regional Areas	Two or more countries in one continent	African countries;[15] European countries[16]
Specific Areas	One region or a small number of region(s) in one country, OR a specific event	Region(s) in one country: Qingdao, China;[17] Hubei, China;[18] Ontario, Canada;[19] Jammu and Kashmir in the northern Himalayan region of India[20] Specific event: A concert at the Royal Albert Hall[21]
Local Areas	Multiple cities/regions in one country	Twenty regions in Italy;[22] Seventeen metropolitan cities in USA;[23] Whole country of Japan;[24] Whole country of Nepal;[25] Multiple provinces in China[26,27]
Global coverage	At least five countries from at least two continents	154 countries studied;[28] Italy, Germany, Spain, France, US, China;[29] China, Switzerland, Japan, Austria, the United States, Brazil, and Russia;[30] Canada, France, India, South Korea, and the UK;[31] France, Germany, Italy, Spain & USA[32]

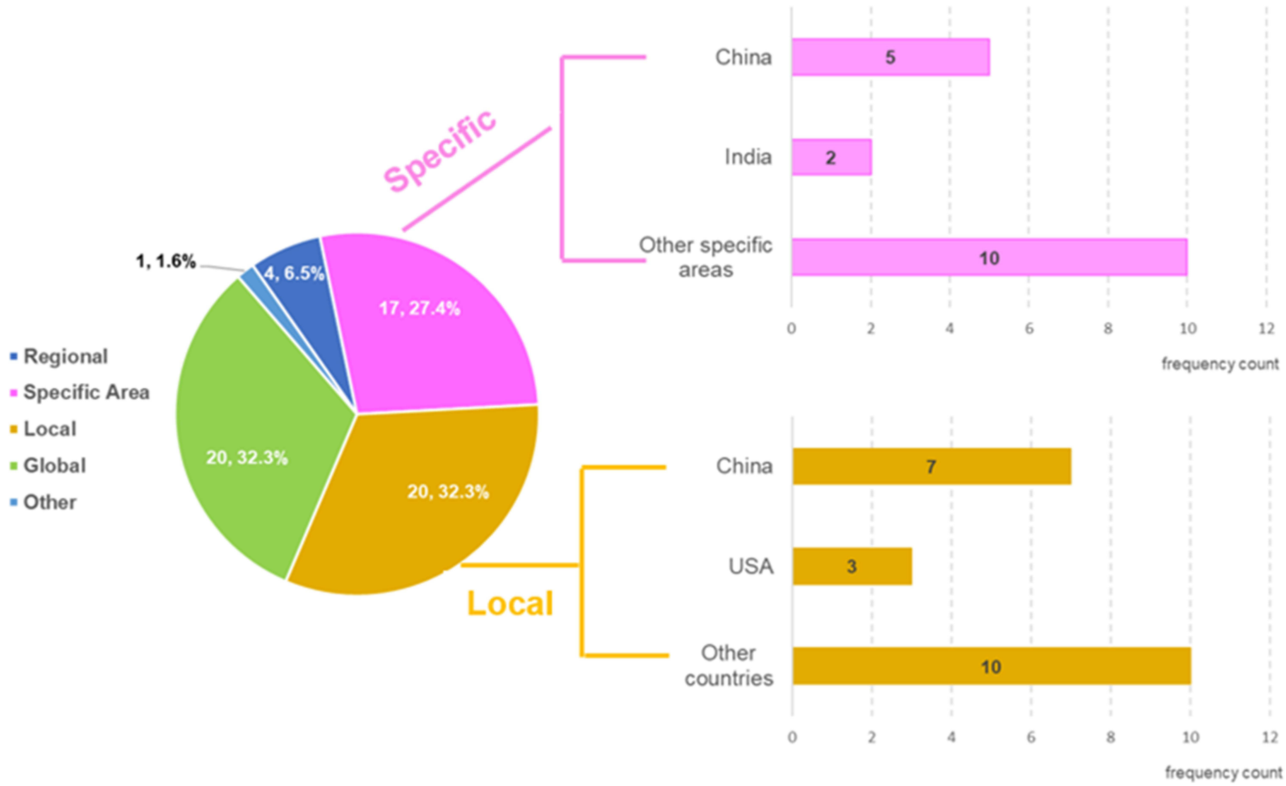


Figure 2 Distribution of the four sizes of geographical area studied (The numbers shown inside/outside the pie chart are the frequency count and the percentage of the 62 articles, respectively.).

As shown in Figure 3, epidemic data was the most common type of variable used, appearing in nearly three-quarters (74.2%) of the 62 included articles, whereas the percentage was less than 50% for each of the other five types of variables. Environmental data were a relatively unpopular variable type and were used in only 9.7% of the 62 included articles.

Figure 4 measures how broadly the different types of variables were used in the 62 included articles (ie, how many types of variables in Table 2 were used). The minimum breadth (the use of only one type of variable) and maximum

Table 3 Examples of the Six Types of Data Represented by the Variables

Data Type	Example
Epidemic Data	Daily & cumulative number of confirmed cases; daily number of new cases; daily and cumulative number of death cases; number of confirmed and death cases per a certain number of people; n-day moving averages of confirmed cases and death cases; case fatality rates; number of sporadic cases imported from other infected areas; clusters of cases detected in well-defined clusters; number of re-emergent cases
Population/ Demographic Data	Total residents living in the study area; population density per km^2; ratio of aging population to total population; percentage of black population/minority population/immigrants; gender; age; income; employment status
Mobility/ Transportation Data	Ratio between commuting flows and employed population; people's mobility patterns; hotspot locations of confirmed cases; mobile phone data on user location information; daily flight-booking data; daily number of passengers on flights from one country to another; inter-city multichannel transportation information; Daily Baidu Mobility Indexes (dBMIs); Tencent-Yichuxing location data
Socioeconomic Data	GDP; public and private debt to GDP; government expenditures to GDP; tourism (contribution of tourism to GDP); inflation rates; unemployment rates (% of the total labor force); percentages of main workers and percentages of literates; prevalence of low income; poverty index; literacy rate; human development index

(*Continued*)

Table 3 (Continued).

Data Type	Example
Survey Data	Online questionnaires with which participants were recruited via weblink, social network, or e-mail; qualitative surveys with in-depth interviews and focus-group discussions; natural survey data of a country
Environmental Data	Annual average of PM10 daily mean concentration; average winter daily mean temperature; daily temperature; night-time light intensity; water sanitation and hygiene; virus concentration in wastewater and river water; ecological footprint (human demand on natural capital)

breadth (the use of five types of variables) were 1 and 5, respectively. Four articles were grouped into "Others" mainly because they lacked enough relevant information to precisely identify the variable types used in their studies.

Approximately 41.9% of the 62 included articles used only one of the six types of variables, as is shown in the upper half of Figure 4. The types of variables used by these 26 articles were epidemic data, mobility/transportation data, and survey data. Epidemic data variables (19 articles) were the distinctly most popular type of variable among the articles using a single type of variable, compared with mobility/transportation data (five articles) and survey data (two articles). More than half (51.6%) of the 62 included articles used two or more types of variables. Use of two types of variables (29%) followed use of a single type of variable as the second most common number of types of variables used in the risk assessment.

Among the 18 articles using two types of variables, the lower half of Figure 4 shows that epidemic data and population/demographic data (eight articles) were the most popular pair, followed by population/demographic data and survey data (four articles).

RQ3: Availability of the Materials Used to Generate Research Outcomes

Every study's data collected and computing codes used to realize research outcomes are essential materials during the development of an article reporting on that research. The left side of Figure 5 summarizes the availability of the data and codes for the 62 articles we reviewed. More than half (54.8%) of the articles we analyzed did not mention whether their data and/or codes had open access. Approximately 11% of them quoted in their data availability statement that interested scholars could request data and codes from the authors. The remaining one-third of the 62 articles provided specific hyperlinks for downloading their materials.

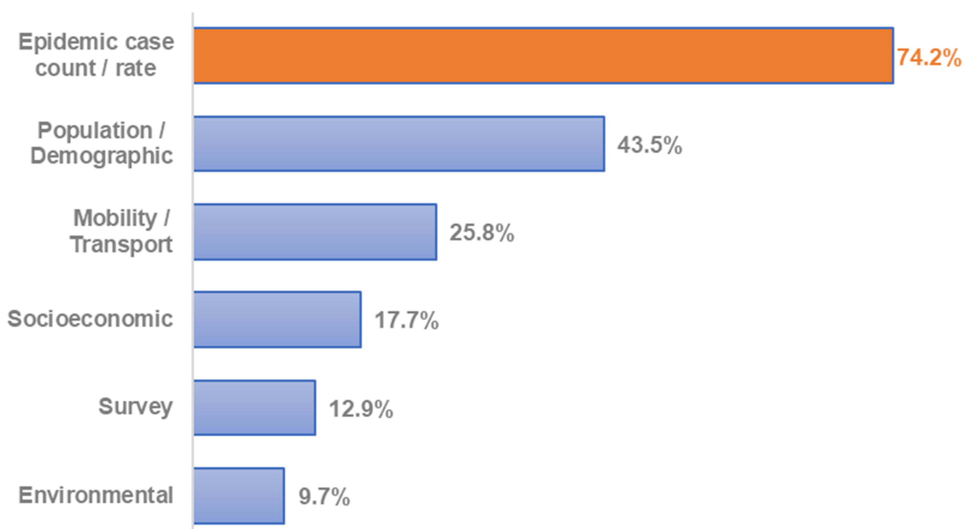


Figure 3 Penetration rate by the different types of variables (= number of articles that used this type of variable/62).

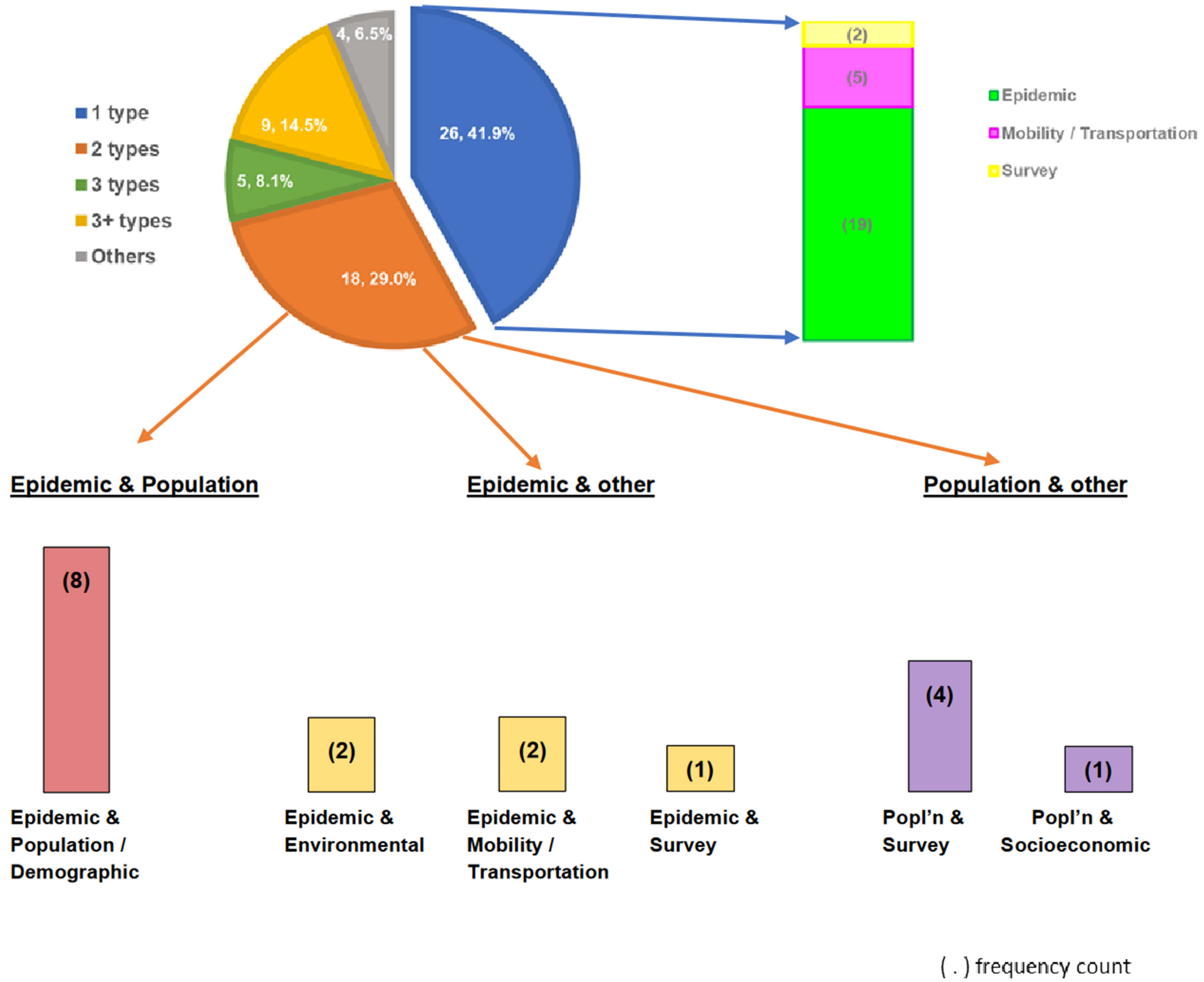


Figure 4 Numbers of the types of variables used by the 62 included articles (Numbers shown inside the pie chart are the frequency count and the percentage based on 62 articles, respectively.).

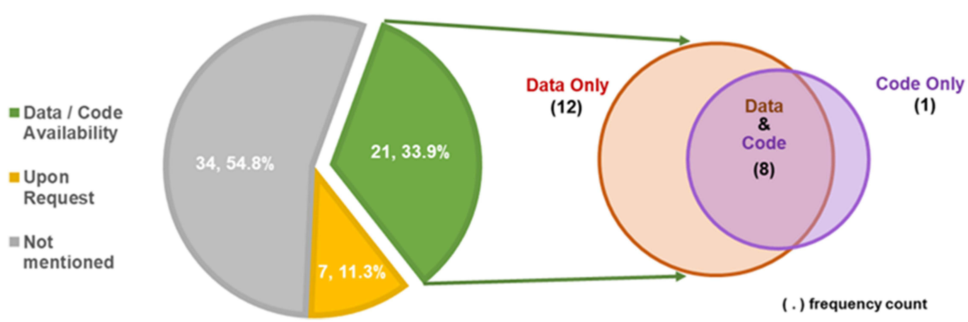


Figure 5 Accessibility of data and codes (Numbers shown inside the pie chart are the frequency counts and the percentages based on 62 articles, respectively.).

The right side of Figure 5 shows the breakdown of the 21 articles that made their data and/or codes available: 20 articles made their data available; nine articles made their codes available; and eight articles made both their data and their codes available.

RQ4: Use of Data-Visualization Techniques

All 62 of the articles we reviewed used tables or charts or both to present their research findings and outcomes. Approximately 80% of them (50 articles) included tables. The percentage for those using charts was even higher, at 90.3% (56 articles). Forty-four of the articles (71%) displayed both tables and charts in their presentation. There are many different data-visualization techniques, and we found that seven types of graphic representation of data were used in the 62 articles: (1) time-series plots, (2) bar charts, (3) scatter plots, (4) box plots, (5) 3D plots, (6) network graphs, and (7) heat maps. These seven data-visualization techniques are detailed in Figure 6.

Of the seven data-visualization techniques mentioned above, three were used in at least half of the 62 included articles: time-series plots (38 articles or 61.3%), scatter plots (33 articles or 53.2%), and bar charts (31 articles or 50%). Box plots and network graphs were less popular data-visualization techniques in our reviewed articles, having been used in only nine articles (14.5%) and eight articles (12.9%), respectively. The relatively low number of articles that presented a network graph was expected because not many of the articles had conducted a network analysis as their research methodology. Figure 7 shows the relative popularities of the different data-visualization techniques.

Figure 8 measures the breadth of the data-visualization techniques usage by the 56 included articles that used charts (ie, it shows how many types of data-visualization each article used). Of those 56 articles, the minimum (using one type) and maximum (using six types of visualization) breadth were 1 and 6, respectively. Minority groups made up two extremes: those using just one type of data visualization technique (7 articles or 12.5%) and those using more than four types (5 articles or 8.9%).

The most common breadth was 2, occupying approximately one-third (19 articles) of the 56 included articles. As shown in the upper half of Figure 8, out of those 19 pairs, only four different pairs of visualization type were used by more than one article. The most common pairs were "Time series plot & Bar chart" and "Time series plot & Scatter plot", with six articles using each of those pairs. The less common pairs, with two articles using them, were "Time series plot & Heat map" and "Scatter plot & Heat map".

The breadth value 3 followed the breadth value 2 and was the second most common size of data visualization techniques used by the 56 articles that used charts. As is shown in the lower half of Figure 8, the most popular triples were "Bar chart & Heat map & Time series plot" and "Bar chart & Heat map & Scatter plot", with three articles using each of those triplets. Another three articles with the breadth of 3 used two of same techniques, "Time series plot & Scatter plot", but their third techniques were different.

RQ5: Research Objectives

We found that the primary research objective of each of the articles could be classified into five major themes (see also Figure 9): (1) COVID-19 risk exposure assessments using risk indicators/indexes or identifying risk factors (22 articles or 35.5%); (2) reviews on the effectiveness of policy measures for COVID-19 control and prevention (11 articles or 17.7%); (3) predictions/estimations of COVID-19-related parameters (10 articles or 16.1%); (4) investigations on the patterns of COVID-19 transmission/geographical spread of COVID-19 (eight articles or 12.9%), and (5) specific-focus articles (11 articles or 17.7%).

Table 4 gives further descriptions of the (1) COVID-19 risk exposure assessments that used risk indicators/indexes or identifying risk factors; (2) reviews on the effectiveness of policy measures for control and prevention; (3) predictions/estimations of COVID-19 related parameters, (4) patterns of transmission/spread of COVID-19 and (5) specific focuses.

RQ6: Research Methodologies

Generally, the articles we reviewed used more than one research method to produce their research outcomes. In each article, we focused on the core aspects of the various methods used, and we identified six core statistical research methodologies from 54 of the included articles: (1) exploratory data analysis (eight articles or 12.9%); (2) network analysis (five articles or 8.1%); (3) time-series analysis (four articles or 6.5%); (4) Susceptible, Infected, and Recovered (SIR)/Susceptible-Exposed-Infectious-Removed (SEIR) Models (seven articles or 11.3%); (5) proposed frameworks/systems (nine articles or 14.5%); and (6) special models/techniques (21 articles or 33.9%). The remaining eight articles (or 12.9%) either provided insufficient information to determine which core methods were used or they used a narrative description/qualitative analysis/context analysis as their core method (Figure 10).

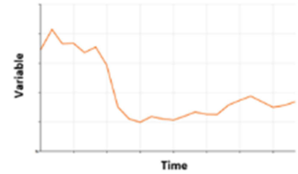
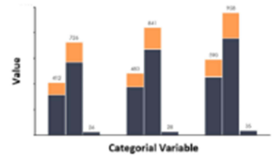
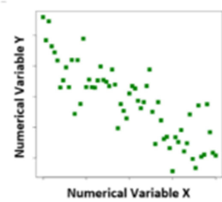
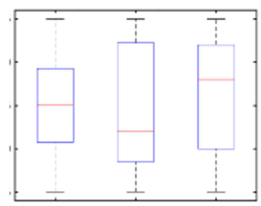
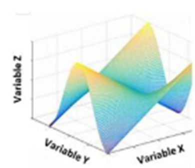
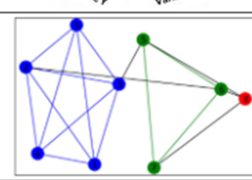
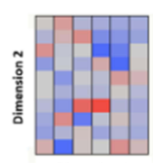
Data Visualization	Description	Icon
Time series plot	A plot displays a line or vertical bar. The *x*-axis plots a series of data points in time order, and the *y*-axis represents the values of the variable of interest.	
Bar chart	A diagram shows one or more categorical variable(s) with rectangular vertical bar(s) or horizontal bar(s), whose height(s) or length(s) is (are) proportional to the value(s) of the variable(s).	
Scatter plot	A scatter plot displays a collection of data points. The position of a data point shows its respective values of *X* and *Y*, representing two numerical variables of interest.	
Box plot	A box diagram displays a vertical rectangular box with lines extending from the upper and lower end of the box. Five summary statistics are shown for a numerical variable: its minimum, first quartile, median, third quartile, and maximum.	
3D plot	A 3D plot displays a three-dimensional surface area formed by three variables of interest.	
Network graph	A network diagram uses lines or edges (the link) to display the relationship or connection of objects of interest (the nodes).	
Heat map	A two-dimensional matrix or heat map uses different colors or shades of one color to display the intensity levels of a measurement.	 

Figure 6 Description of seven common data-visualization techniques.

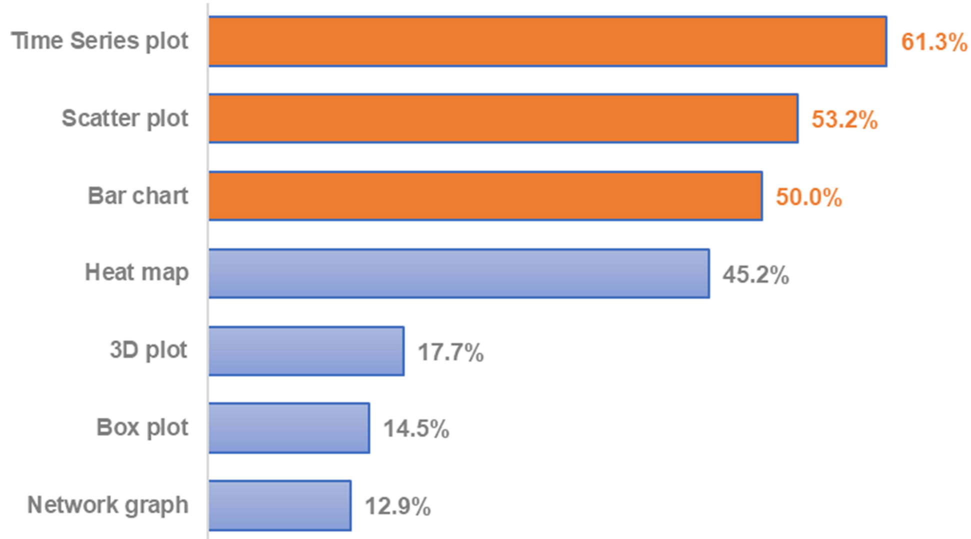


Figure 7 Penetration rate by different data-visualization techniques (= number of articles that used the specific data visualization technique/62).

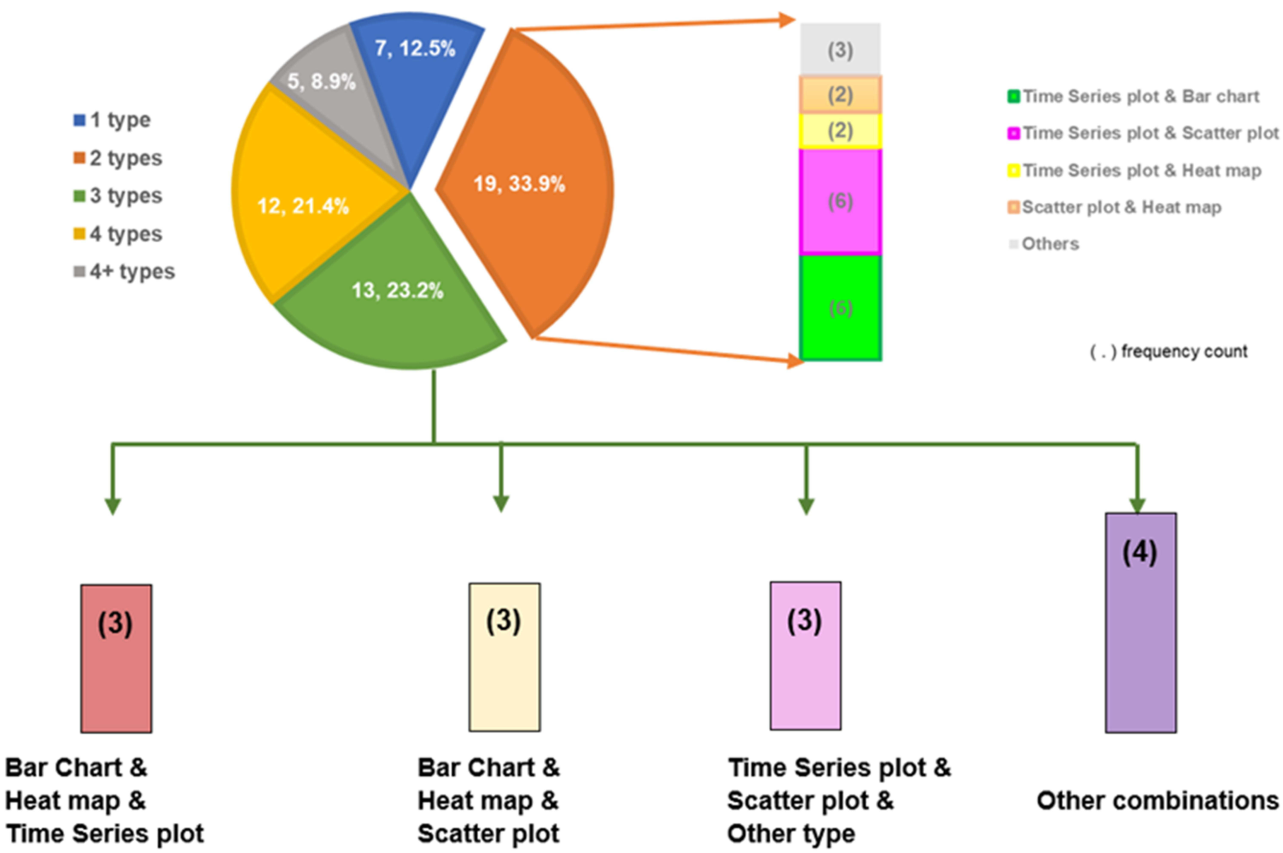


Figure 8 The number of types of data-visualization techniques used by each of the 56 articles that used charts. (Numbers shown inside the pie chart are, respectively, the frequency count and the percentage of the 56 articles that used charts.).

Methodology outlines for the research methodologies for exploratory data analysis, network analysis, time-series analysis, and SIR/SEIR models are summarized as group levels in Table 5. The proposed framework/system and special model/technique approaches are described individually in Tables 6 and 7, respectively, because they are quite unique in nature.

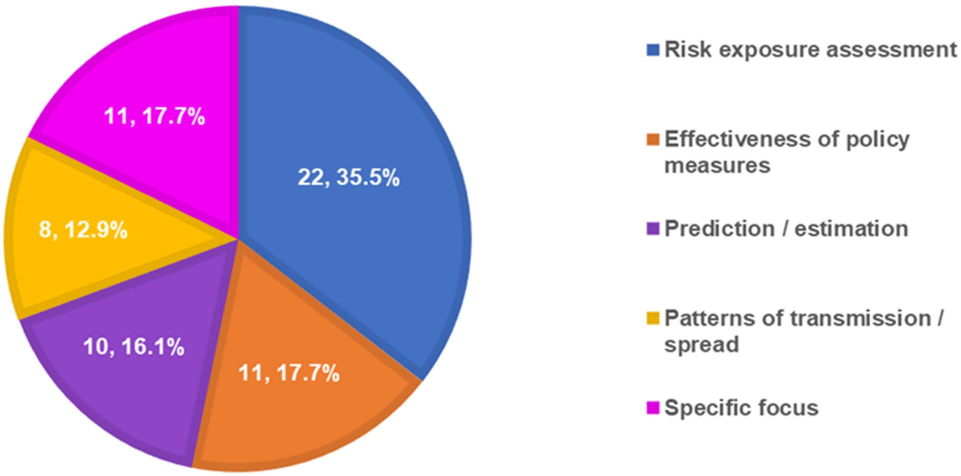


Figure 9 Breakdown of the 62 articles by research objective. (Numbers shown inside the pie chart are respectively the frequency count and the percentage of the 62 articles.).

Discussion

Principle Findings

From our classification, which we derived solely from observing the nature of the various research questions, we found that the 62 included articles reflected a wide variety of research focuses on different aspects of the COVID-19 pandemic risk assessment. With the exception of the research question "Availability of Materials to Generate Research Outcomes", each research question classification contained at least four class types. Except epidemic data (74.2% or 46/62) in "Types

Table 4 Further Descriptions of the Research Objectives

Research Objective	Number of Articles	Index of Articles
Risk exposure assessments by using risk indicators/indexes or identifying risk factors		
For an individual country	11	[22,25,27,33–40]
For multiple countries	5	[28,41–44]
For public health care system/staff	3	[15,45,46]
Related to building usage in confined spaces	1	[47]
Regarding overseas imported COVID-19 on ocean-going ships	1	[48]
For the human risk of infection due to inadvertent ingestion of water during swimming in a river	1	[49]
Total	22	
Reviews of the effectiveness of policy measures for control and prevention		
Evaluation of the effectiveness of intervention strategies (eg, one-way movement versus unrestricted movement, frequency of leaving designated work locations for breaks, distance learning in primary and secondary schools, and so on)	2	[50,51]
Evaluation of the control and prevention policies by government/policymakers	8	[18,24,29,37,52–55]

(*Continued*)

Table 4 (Continued).

Research Objective	Number of Articles	Index of Articles
Review of existing health security capacities (in light of the COVID-19 outbreak) against public health risks and events	1	[56]
Total	11	
Predictions/estimations of COVID-19-related parameters		
Number of new infections/growth of infections	2	[21,57]
COVID-19 attributable mortality/risk of death among confirmed cases	2	[58,59]
Future trends of confirmed cases	2	[20,31]
Time lag between peak days of cases and deaths	1	[30]
Probability of occurrence of extreme epidemics	1	[60]
Probability of COVID-19 resurgence caused by work resuming (and schools reopening)	1	[61]
Potential risk associated with releasing travel restriction measures between countries	1	[62]
Total	10	
Investigations on the patterns of COVID-19 transmission/geographical spread of COVID-19		
Statistical model development to investigate the pattern of transmission/geographical spread of COVID-19	5	[19,26,63–65]
Study on the geographic risks of the COVID-19 transmission by countries/regions	3	[66–68]
Total	8	
Specific focus		
Impacts of vaccination/face masks	3	[16,32,69]
Visualization of the risks from the COVID-19 pandemic	3	[17,70,71]
Narrative description of the development of COVID-19, and lessons learnt	3	[72–74]
Performance level of detecting early-warning signs	2	[23,75]
Total	11	

of Variables Used" and time-series plot (61.3% or 38/62) in "Use of Data-Visualization Techniques", the distribution of class types was quite diversified, with no distinct class type that was prominent.

The study locations examined by these 62 included articles comprised worldwide coverage. Four class types, based on the size of the geographic areas studied, were identified: Local areas (32.3% of articles), Global coverage (32.3% of articles), Specific areas (27.4% of articles), and Regional areas (6.5% of articles). Seven out of the 20 local-area articles and five out of the 17 specific-areas articles focuses in China. No other single country has such a high frequency of appearance. The study locations of the remaining, much larger proportion of articles were scattered across the globe, either in a single country other than China or in a mix of different countries.

In the era of big data, we are not surprised that as many as six different types of data were used in the 62 articles. As was suggested by the titles of the articles, epidemic data were the most widely used type of data (in 74.2% of articles), while environmental data were the least frequently retrieved type of data (9.7% of articles). Articles using a mixture of types of data (32 articles) did not substantially outnumber those using just one single data type (26 articles), thus

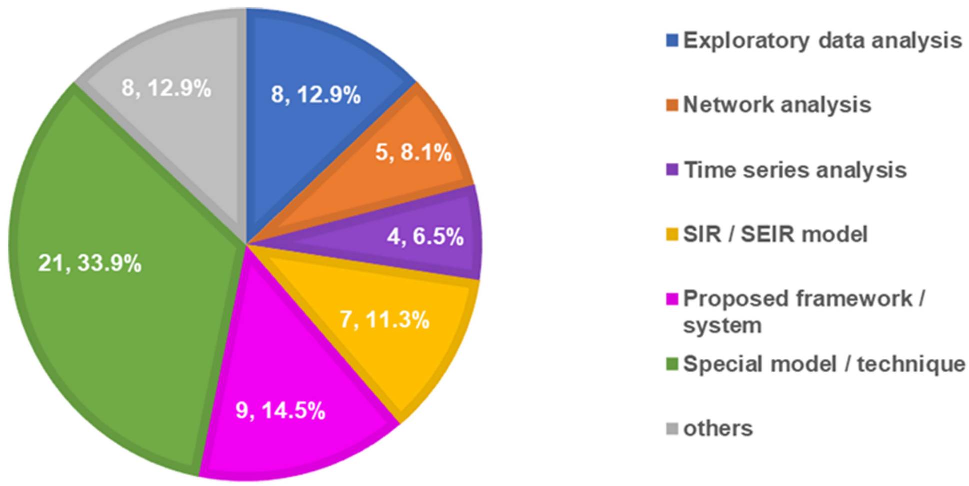


Figure 10 Types of research methodologies used by the 62 included articles. (Numbers shown inside the pie chart are the frequency count and the percentage of the 62 articles, respectively.).

suggesting that fully utilizing the diversity of available types of data might not be a prevalent phenomenon in COVID-19 pandemic research work.

It goes without saying that thorough documentation, such as making one's research data and codes available to readers and other researchers, is essential in published papers in order to facilitate the understanding and the

Table 5 Methodology Outlines of the Exploratory Data Analysis, Network Analysis, Time-Series Analysis, and SIR/SEIR Models

Methodology Outline	Number of Articles	Index of Articles
Exploratory data analysis		
Variables in the research datasets were converted into different categorized data, new indicators were developed using ratios, percentages, and sums, and the results were presented through descriptive tables and charts	3	[56,66,76]
Graphical trajectory analysis was used to estimate the time lag between peak days of cases and of deaths.	1	[30]
Probability distribution was used to estimate the probability of occurrence of extreme epidemics /COVID-19 resurgence	2	[60,61]
In addition to descriptive tables and charts, other statistical analysis were also used, such as ANOVAs, regressions, and the like.	2	[39,51]
Total	8	
Network analysis		
A co-occurrence matrix was constructed of policy-issuing agencies to sketch the network structure, then a collaborative network was drawn to track the role changes of agencies, and finally an "agency–topic" network was built to reveal the policy focus of each agency	1	[52]
A dynamic pandemic network was constructed of connections/graphs by linking two geographical areas if the correlation of changes in the number of confirmed cases was greater than a threshold value	3	[53,62,71]
A multilayer transportation network was constructed with cities as nodes, connected by four means of inter-city transportation: Air, Bus, Rail, and Sail	1	[27]
Total	5	

(*Continued*)

Table 5 (Continued).

Methodology Outline	Number of Articles	Index of Articles
Time series analysis		
The autocorrelation at-lag-1 and standard deviations of rolling windows were examined for use in early warning signal detection	1	[23]
Time correlations between air traffic and COVID-19 transmission and mortality were compared, where time correlations were performed using Pearson correlation coefficients compatible with the linear relationships visually observed with scatterplots	1	[69]
An autoregressive integrated moving average model ARIMA(p, d, q) was adopted where p and q were the order of the AR model and the MA model, respectively, and d was the level of differencing	2	[31,75]
Total	4	
SIR/SEIR models		
A contact tracing/network method with a SIR (Susceptible, Infected, and Recovered) model was incorporated to develop an enhanced spatio-SIR model/spatial agent-based SIR model	2	[36,50]
A Susceptible, Exposed, Infectious, Recovered (SEIR) model was constructed and differential equations were used to obtain the relationships of model parameters	2	[32,54]
The basic SIR model (Susceptible, Infectious, Recovered) was modified by considering more parameters, such as having been vaccinated, and whether a recovered person was reinfected, and using additional techniques such as differential equations and the Kendall ranking method	3	[16,20,65]
Total	7	

Table 6 Methodology Outline of the Proposed Frameworks/Systems Approach

Proposed Frameworks/Systems	Structure Outline	Index of Articles
A novel data-driven framework was created to assess the a-priori epidemic risk of a geographical area	Risk index was evaluated as a function of Hazard (H), Exposure (E), and Vulnerability (V)	[22]
A framework was created to model environmental exposure at the population level	Three stages were used: (1) individual vector fields were defined, (2) these individual vector fields were accumulated, and (3) indicators to evaluate the environmental exposure were proposed	[34]
A COVID-19 risk-based assessment (CRAM) framework was created for analyzing COVID-19 risk in various geographical areas	Three steps were identified: (1) GIS layers of various data were generated, (2) hazard and vulnerability maps were integrated, and (3) risk mapping for decision making was conducted to prioritize COVID-19 risk areas	[35]
A three-stage machine-learning strategy was used to classify country-level risk based on three types of risk: risk of transmission, risk of mortality, and risk of inability to test	First stage: four risk groups of countries were created, based on country-level COVID-19 information Second stage: country-level geopolitical and demographic attributes were selected for the prediction of three types of risk Third stage: leave-one-country-out cross-validation was employed to find the strongest model for each type of risk	[42]

(*Continued*)

Table 6 (Continued).

Proposed Frameworks/Systems	Structure Outline	Index of Articles
A decision-making scheme was created to assess the risk of continuing transmission for African countries	First, a country was assigned to a transmission scenario and the health system response's capacity of that country was assessed. Then, a matrix combining the transmission scenario and health system's response capacity was used to estimate the level of risk	[15]
A new privacy-preserving and inclusive system (PanCast) was created for epidemic risk assessment and notification	The system components included hardware devices, installation and collection, testing and uploading, and risk notification. A spatiotemporal epidemic model was used to generate notification for contact-tracing actions	[38]
A new Multi-Criteria Decision Making (MCDM) method, AHPSort II-SW, was created to assess internet public opinion risk levels for public health emergencies	First step: a multistage risk classification model of Internet public opinion was built to monitor the risk levels of Internet public opinion for public health emergencies, with long time extensions Second step: AHPSort II and Swing Weighting (SW) and a proposed AHPSort II-SW method were combined to grade the risk levels of Internet public opinion in public health emergencies Third step: The new method was applied to the public opinion risk rating of Microblog platform	[46]
A framework for the COVID-19 risk assessment was created by incorporating the COVID-19 cases, exposure, immigration (quarantined data), public health facility, and population density data	The framework included personal risk and regional risk assessment. Personal risk was calculated by an equation consisting of COVID-19 transmission risk, public health risk, and socioeconomic risk. Regional risk focused on food productivity and supply chain network in a region	[25]
A framework was generated to dynamically assess the infection risk on board ships, based on a data-driven approach	First step: ship "stop" events were detected with the ST-DBSCAN algorithm Second step: hoteling stops were extracted from detected stops, based on distances between their locations and land boundaries Third step: hoteling stops were mapped to their nearest ports and countries based on AIS data Fourth step: a COVID-19 exposure index was calculated to evaluate the risk of a ship being infected by COVID-19 Fifth step: the infection risk of a ship was categorized into high, middle, and low levels	[48]

Table 7 Methodology Outline of the Special Models/Techniques Approach

Special Models/Techniques	Outline of the Special Models/Techniques	Index of Articles
Pandemic Risk Exposure Measurement (PREM) model	Exploratory factor analysis was used to develop the model, and Cronbach's Alpha assessed the model's reliability	[28,41]
Optimized gravity models and spatiotemporal risk modelling	Geographically and temporally weighted regressions (GTWR) were used to build the models, and kernel density estimations (KDE) based on the Gaussian kernel function were used to spatially smooth the epidemic data	[17]
Multidimensional item response theory, confirmatory factor analyses, and structural equation modelling	These techniques were used to construct and assess the quality of the proposed pandemic-risk-perception scale	[33]

(*Continued*)

Table 7 (Continued).

Special Models/Techniques	**Outline of the Special Models/Techniques**	**Index of Articles**
Semi-quantitative risk assessment model	The methods of Brainstorm, Literature study and Analytic Hierarchy Process (AHP) were used for risk factors selection and model construction A nonparametric statistical method Weighted Rank Sum Ratio (WRSR) were used for risk level evaluation	[45]
Total Risk Assessment (TRA) evaluation tool and Infected Patient Ratio (IPR) tool	Seven indicators with a 5-point scale were used for each indicator to develop TRA scores The number of confirmed cases resulting from one primary infector were calculated during the incubation period, to develop IPR values	[29]
ST (seeding time) and DT (doubling time) Model	A 2D plane was divided into four quadrants by using the mean ST and mean DT, with ST on the *x*-axis and DT on the *y*-axis to construct the model Sensitivity analyses were conducted to verify and validate the model	[43]
Conceivable mathematical model - Accelerated Phase Modelling	The generic framework of the Stockholm Environment Institute (SEI) Epidemic–Macroeconomic Model was considered in the model development stage The least-squares method, nonlinear regression (eg, low-degree polynomial), derivation (function) method, and the tangent method were used to obtain the estimated parameters	[63]
Attributable Mortality Model (AttMOMO)	A time series regression model on the total number of deaths was decomposed into those attributable to one infectious disease with no excess temperature (base model) or other infectious disease circulating, and those attributable to deaths due to excess temperatures and benign effects of other infectious diseases	[58]
Static and dynamic risk assessment models	The gravity model was used to develop the static model The Cox proportional hazards framework with a time-varying hazard function was used to replace the constant parameters of the static model to build the dynamic model	[18]
Occupant exposure model (EXPOSED)	The crowd model was used to develop the model in eight steps, with the first step to define the crowd movement scenarios and the final step to calculate global assessment of occupant exposure G	[47]
Rasch model and Bayes' theorem	The online Rasch rating scale model (developed codes available online) was used to obtain Rasch scores The Bayes theorem was applied to estimate the adjusted case fatality rate (CFR) for countries/regions	[67]
Bayesian hierarchical spatiotemporal model	Four models were built – one that was space-time separable and three that were space-time inseparable The Poisson distribution was used as the likelihood function in the data model A multivariable logistic regression was used as the process model The Markov Chain Monte Carlo method with different initial values was used to fit each model The Joinpoint Regression Program, which uses the least-squares regression method, was used to find the best-fit line from the temporal (weekly) pattern	[19]

(*Continued*)

Table 7 (Continued).

Special Models/Techniques	Outline of the Special Models/Techniques	Index of Articles
Mixed-effect models	The generalized form of linear regression was used to analyze experimental outcomes of within-subjects (time points) and between-subjects conditions (pre- and post-visualization exposure)	[70]
Analysis of covariance (ANCOVA)	An ANCOVA was used to examine any significant difference in average county death rates by one variable, while adjusting for other variables	[68]
TVP-VAR model	Dynamic net pairwise dynamic directional connectedness, based on the TVP-VAR model, was used to construct dynamic contagion indexes across countries	[64]
Multiplicative exponential model and Spatio-temporal model	First, a multiplicative exponential model was used to model the effect of outflow on infection Next, a nonlinear least-squares method (Levenberg–Marquardt algorithm) was applied to estimate the parameters of the model, with confirmed cases as the dependent variable Last, a Cox proportional hazards framework was used to replace the constant scaling parameter of the model with a time-varying hazard rate function to develop another model: a spatiotemporal model	[26]
Model-based approach	The nonparametric *k*-nearest-neighbor (kNN) approach was used to estimate the number of infectious participants A compound Poisson distribution was used to calculate the effective number of participants at risk in an event	[21]
Dynamic infection model	Well-known statistical physics that was fundamentally different from classic infectious disease theory was used with seven conventional and physically reasonable assumptions on rate and distribution of disease infections to develop the model	[57]
Time-delay distribution from illness onset to reporting and death	The gamma distribution was used to fit the time-delay distribution from illness onset to reporting An exponential growth model and lognormal distribution were used to model the time-delay distribution from onset to death	[59]
GeoDetector model and the decision-tree model	A set of statistical methods were used to detect the spatial heterogeneity/consistency of the spatial distribution patterns between the dependent variable and the independent variable The machine-learning method of the decision tree was used to calculate the exposure risk of infection	[40]

interpretation of one's research outcomes. Approximately one-third of the 62 articles we reviewed (21 articles) gave clear instructions for open access to the data and the codes for their studies. Even if counting as open access the seven articles that offered possible accessibility to their data and codes upon request from the corresponding authors, more than half of the 62 included articles (34 articles) still did not provide this option. We understand that full transparency of data and codes may not always be possible, due to competing interests or other sensitivity issues, but it is worthwhile for authors to consider at least a limited disclosure of their research materials in order to improve the reliability and the appropriate use of research outcomes by policymakers and healthcare-related professionals.

Use of tables and charts certainly helps explain the process of the research work clearly and effectively to the readers. From the initial stage of data exploration to the later stage of presenting the research findings, we saw many tables and charts in different forms and types. Approximately 80% of the articles (50 articles) used tables and even more articles (56 articles or 90.3%) used charts, whereas 44 articles (71%) used both. We observed seven different types of charts, and as expected, time-series plots were the most common type (used by 38 articles or 61.3%) because the data under study were the time patterns of several waves of COVID-19 transmission. Two special chart types that may not be found commonly in most other studies are particularly useful for visualizing the dissemination of the COVID-19 pandemic: heat maps (used by 28 articles or 45.2%), which displayed the severity of the infection by areas, and network graphs (used by eight articles or 12.9%), which showed the COVID-19 connectedness using straight lines between different places. For the 56 articles using charts, a vast majority (49 articles) used more than one type of chart in order to broaden their visualization effects.

The presumably hot objective of "risk exposure assessment by using risk indicators" did not draw overwhelming interest in the 62 included articles. Although it had the largest proportion (22 articles or 35.5%) of articles, the proportion was smaller than 50%. In addition to risk exposure assessment by using risk indicators, four other research objectives (each with a greater than 10% proportion of the articles) were as follows: effectiveness of policy measures (17.7%), prediction/estimation of COVID-19-related parameters (16.1%), patterns of COVID-19 transmission (12.9%), and specific focuses (17.7%). Given the variety of research objectives in the 62 included articles, policymakers, public health officials, and health-care professionals are urged to rely on the synthesized findings of this systematic review to meet various purposes, such as evaluating the effectiveness of current public health measures, making informed decisions on policies for prevention and control, clinical practices and further research[77] for early detection of an outbreak, better preparation, and burden reduction on public health systems in the event of new waves of infectious disease transmission.

No research methodology was dominant in the 62 articles – in contrast, many different methods were employed, as shown in Figure 10. One common observation was that, no matter which methodology was employed (except for the six articles using either a narrative description or context analysis), most articles applied inferential statistics analyses such as factor analyses, time-series analyses, regressions, Bayesian inferences, and the like, to generate their research outcomes. Their process flows were clearly outlined, and their research methodologies were well documented. Such thorough documentation definitely increases the credibility of articles,[78] giving full knowledge of what has already been done,[79] and facilitating others' ability to replicate research outcomes, with high confidence for the appropriate use by interested parties.

Systematic Review

For policymakers having an interest in topics, which requires reviewing lots of primary papers and articles in a standardized manner, we suggest the following five key stages. First of all, setting up the objectives by clearly pre-defining specific research questions in the context of what are already known. Second, identifying an explicit and reproducible methodology describing eligibility criteria and search strategy for finding relevant research and collecting data. Third, specifying the methods used to assess the validity of the selected information such that they meet the eligibility criteria and how to identify potential risk of bias such as selection bias on target population, performance bias on treatments and reporting bias on result findings. Fourth, providing pre-planned methodological and analytical approach on how to analyze quantitative data and synthesize qualitative evidence. Lastly, describing how to interpret the results, summarize the findings and recommend actionable plans.

Limitations and Future Research

Some limitations apply to this systematic review. First, it is possible that some relevant studies could not be included. Even though we used a comprehensive and highly relevant source, WHO COVID-19 research database, there may still be chances that some relevant articles were not captured. Another possibility for missing some relevant articles is that certain articles were screened out by the exclusion criteria such as non-English language articles and articles with no open/free access. In addition, the number of included articles in this systematic review might be considered to be not sufficient because of the limited number of articles that met the eligibility criteria. Unlike survey sampling, there is no universal measurement to determine the appropriate size for systematic review. When retrieving published studies of systematic review, it is common to find that the size of the final list is usually less than 100, some may even be less than 30. So, we believe that this limitation does not affect the validity of our findings.

Future research should continue to track the latest development of COVID-19 as it progresses. Two new variants (Omicron and Arcturus) have emerged after the date of searching relevant studies for this systematic review. In addition to capturing more recent relevant articles that studied the new waves of transmission, a critical appraisal tool should be developed in order to assess the quality of the included articles from different assessment criteria such as study design, statistical analysis, and outcomes. This helps to quantify the strengths and weaknesses of the included articles and hence facilitate more in-depth discussion and better interpretation of the findings.

Conclusions

The impact of the COVID-19 pandemic has been enormous, presenting unprecedented challenges to public health. Therefore, researchers conduct risk assessment based on available data and methods to identify risk factors and/or study their effects and consequences. Although we have entered the post-pandemic period for COVID-19, history tells us that we should continue to stay vigilant against both the emergence of a new variant of COVID-19 and also of a new infectious disease.

This systematic review gathered relevant research works about the global COVID-19 pandemic risk assessment by conducting an extensive systematic search in the WHO COVID-19 Research Database, and we here provide useful synthesized findings of what has been done to evaluate the COVID-19 pandemic risks. Policymakers and those who are responsible for public health can refer to our detailed summary of the various research objectives, which we have classified in this systematic review, and can learn from one or more of them depending on the priorities of their country. This information can support informed decisions and plans for informed actions to analyze and monitor the spread of new infectious diseases that are likely to arise in the future.

Abbreviations

PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; WHO, World Health Organization.

Data Sharing Statement

The authors confirm that all articles identified through searching WHO database: Global research on coronavirus disease (https://search.bvsalud.org/global-literature-on-novel-coronavirus-2019-ncov/) from its inception to 12 July 2022 and all screened articles are freely available to public at the time of writing by accessing the website (assessed on 20 July 2022).

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Disclosure

The authors report no conflicts of interest in this work.

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