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ORIGINAL PAPER

Measuring hospital care resilience: a systematic literature review

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Abstract
The recent Covid-19 pandemic has shown how even high-performing healthcare systems are often unprepared to cope with sudden and unforeseen surges in demand for healthcare services, drawing further attention on crucial factors ensuring their resilience in the face of extreme disruptive events. Despite extensive efforts to define health system resilience, a lack of consensus persists, making it difficult to operationalize the existing conceptual frameworks and to guide policy makers in developing adequate response strategies. Grounded on this, the present paper aims to systematically review how hospital resilience has been measured in high-income countries. Particularly, we intend to map out the different indicators and metrics used to quantitatively assess the hospitals' capacity to proactively face sudden health shocks, which can put clinical activity under pressure and at risk of disruption. Adhering to PRISMA guidelines, a systematic literature search was conducted until March 2023, by combining three databases. The review identified 1,261 studies of which 45 studies met the eligibility criteria. We found a wide range of methodological approaches that shared a narrow focus on single aspects of hospital resilience, without being able to measure it comprehensively and systematically and without accounting for its dynamic and feedback loop nature. Specifically, most of the studies looked at how to measure hospitals' capacity to absorb the shock and adapt to it, while almost neglecting their transformative capacity as well as the legacy or enduring impact of shocks.

Keywords Hospitals · Resilience · Health shock · Indicator · Metric

JEL H51 · I10 · I18

Introduction

The Covid-19 pandemic threatened the health and socio-economic well-being of people across countries, showing how even previously high-performing health systems were not well-equipped to cope with sudden surge in demand for healthcare services, due to the infectious disease epidemic [1]. This recent experience, together with other disruptive events of the past two decades (e.g., the 2008 financial crisis, the 2014–2016 Ebola outbreak), has drawn attention to the resilience of health systems, meant as the ability of health actors, institutions and populations to respond to any kind of external shock while maintaining their critical functions [2].

However, much of the knowledge about resilience can be traced back to the field of physical science, where it indicates the property of an elastic material (such as rubber or animal tissue) to absorb energy (such as from a blow) and release that energy as it springs back to its original shape [3, 4]. Then, the concept of resilience has been extended to a variety of other fields, including ecological science, to mean the capacity of a system to absorb a shock and bounce back to an equilibrium point after having experienced a disruptive event [5–7].

The notion of resilience has been recently introduced in the public health debate, as policymakers and researchers recognized a series of political and technical deficiencies in tackling major health crises and realized the urgency to strengthen health systems to make them more "resilient" to an array of potential sources of future shocks. In the absence of a general consensus on the exact scope of the concept

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[8–11], most definitions of resilience share the idea of health systems as complex adaptive systems [12], grounded around three different capacities [13]: the absorptive capacity that indicates the capacity of a health system to continue to provide the same level (quantity, quality and equity) of basic healthcare services and protection to populations despite the shock, using the same level of resources and capacities; the adaptive capacity that means the capacity of healthcare actors to deliver the same level of healthcare services with fewer and/or different resources, which requires making organizational changes; finally, the transformative capacity that relates to the ability of the system to transform its functions and structure to respond to a changing environment.

The above notion has many advantages among which that of considering the resilience of health systems as the capacity (partly innate and partly to be acquired and nurtured) to maintain or improve their performance in the face of a shock rather than as an objective in its own [14]. In this sense, the health system's bouncing back does not refer necessarily to a return to the original (pre-shock) state, but it may require the transformation to a new, improved state [15]. Furthermore, the definition adapts to the local health systems' needs and context-specific factors.

Nonetheless, the recent health policy and systems research literature has embraced the complex and time-dependent nature of resilience, highlighting the limitations of the previous conceptual framework. Particularly, defining resilience solely based on the three above-mentioned capacities (i.e., absorptive, adaptive and transformative) is somewhat limiting as this focuses only on one stage of the response cycle to a shock, that of the shock impact and management, without considering the other three stages, i.e. the preparatory phase (pre-shock), the stage of shock onset and alert, and that of recovery and learning (post shock) [16]. Therefore, in this study we prefer to adopt the definition of health systems resilience developed by the European Observatory on Health Systems and Policies [16], where health system resilience is defined as the "health system's ability to prepare for, manage (absorb, adapt, and transform) and learn from a sudden and extreme disturbance". The broad scope and comprehensiveness of this conceptual framework ensure its relevance and adaptability across different settings.

The existence of a wide variation in definitions of health system resilience has curbed researchers' attempts to back-test the analytical frameworks empirically, which is ultimately reflected in a fundamental lack of consensus on how to operationalize the concept by health policy-makers. Thus, despite a huge number of theoretical (systematic and non-systematic) reviews on what exactly constitutes a resilient health system, empirical literature on how resilience-related features can be measured and assessed is still limited. Indeed, strengthening the resilience of health systems in the response to future unexpected shocks does not only require identifying a list of health system resilience-enhancing factors but also to acquire access to data, at national and sub-national levels, to assess the presence/absence of these factors over time through appropriate quantitative metrics.

This paper aims to achieve multiple objectives. First, it seeks to map the existing literature on hospital resilience indicators, systematically categorizing the metrics and approaches used in prior studies to assess hospital care resilience. This includes evaluating resilience during different phases of health shocks and across various dimensions, such as mortality rates and waiting times. The review also considers suggested methodologies that, while not resulting in fully developed indicators, provide valuable frameworks or approaches for creating such metrics, thereby expanding the range of practical tools for measuring resilience. Second, it summarizes the main results obtained from applying these metrics to different healthcare systems, highlighting the strengths and weaknesses of these systems. For example, it investigates which specialties have been most affected by Covid-19, offering insights into system vulnerabilities. Finally, the paper examines the data sources and data requirements necessary to construct each metric, providing a practical understanding of how these indicators can be operationalized. By addressing these aspects, the paper aims to offer a comprehensive understanding of hospital resilience and its practical implications for health system performance.

Our systematic review is overall close in spirit to the work of Fleming and colleagues [17], although some important differences need to be emphasized. Indeed, we share with them the attention on the metrics used in high-income countries to measure the vulnerability and reaction capacity of healthcare facilities to disruptive events, but we only consider quantitative (and not also qualitative) indicators, highly adaptable to various contexts, and restrict the scope only to health shocks. Furthermore, the focus here is on hospitals as they are frontline healthcare delivery points when health shocks such as pandemics cause a sudden surge in demand for healthcare services. In fact, their failure to cope with high peak flows can cause disruption to their activity and ultimately lead to the collapse of the entire healthcare system as hospitals serve as providers of last resort for many healthcare services.

Methodology

A systematic review was performed in line with the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [18].

Different researchers jointly developed, iteratively tested, and refined the search strategy to capture the largest number of relevant papers on hospital resilience indicators and measures, published in peer-reviewed journals. Indeed, considering the quantitative nature of our systematic review, we decided to exclude grey literature (e.g. conference proceedings, dissertations, working papers, government reports) because of quality concerns as it is usually not subject to a formal peer review process. This decision influenced our search strategy and database selection. While this approach may have omitted some relevant sources (e.g., government reports), we mitigated this limitation through a snowballing process. Contributions retrieved this way were assessed using our standard selection criteria but were ultimately excluded, as they did not propose or suggest any quantitative measures, and therefore outside the scope of the review.

Three databases were combined to search our relevant literature: Web of Science, Ovid Medline and Scopus. The search was conducted in March 2023, with no limitation on the year of study, using the following search terms on abstract, title and keywords: 'hospital', 'health system', 'resilien*' or 'stress test*' or metric* or indicator* or assess* or measur* or quantif*, and 'shock' or their synonyms.[1] Specifically, for the purpose of our systematic review, as far as Web of Science and Ovid Medline are concerned, we adapted the search strategy employed by Fleming et al. [17] to limit the search to hospital resilience but also to include studies on everyday resilience (e.g., seasonal flu). Additionally, drawing from Tan et al. [19] we constructed our search string on Scopus to meet the two above-mentioned objectives. First, since we were mainly interested in assessing the drivers/determinants of hospital resilience, regardless of the database, keywords such as 'indicator' 'assess' 'measure' were used to restrict the literature search to quantitative studies. Quantitative studies, which rely on numerical data and standardized methodologies, can be adapted to almost any context, providing metrics that enable large-scale analysis and cross-country comparisons of different health systems, regardless of local differences. Conversely, qualitative studies, often based on surveys or interviews, offer deeper, context-specific insights (e.g., by examining organizational aspects or staff behavior). However, their findings are more context-dependent, which can limit their external validity. For this reason, we chose to focus exclusively on quantitative studies, although combining both approaches would offer a more comprehensive understanding of the phenomenon. Second, search terms combination varied according to the dataset to deal with the peculiarities of each data source and to better exploit its advanced search tools. Furthermore, we consulted the three datasets in complementarity, with the aim of capturing all the existing peer-reviewed literature on hospital resilience.

The database searches yielded 1,208 articles. These were complemented with other 53 contributions through backwards and forward snowballing, thus reaching a total of 1,261 papers. Starting from these, we used the screening software Covidence[2] to remove 65 duplicates (further 4 duplicates were removed manually). Additional 16 papers were eliminated because abstracts were not available. The PRISMA chart (Fig. 1) depicts how information flows through the different phases of our systematic review, thus allowing to identify the final sample for both title/abstract and full-text screening.

After duplicates and ineligible references were excluded, title and abstract screening for the remaining 1,176 papers were conducted independently by two reviewers, based on predetermined inclusion and exclusion criteria. A third reviewer was involved in case of disagreement between the first two reviewers. Title/abstract included studies had to be published in scholarly peer-reviewed journals and written in English. Furthermore, they needed to quantitatively measure hospital resilience or at least to suggest—while not developing, applying, or collecting—potential indicators or metrics.

Finally, studies were also excluded according to the following criteria:

1) exclusively referred to low-and-middle income countries[3] (with reference to the United Nation classification of economies in transition and developing economies[4]). We decided to leave out these countries for several reasons. First, most of them manage infectious diseases that are instead under control in high-income countries. Second, even when the health shocks are like those in developed economies, the specific characteristics of the health systems of low-middle income countries mean that in these the concept of hospital-care resilience can take on a peculiar connotation that is ill-suited to the context of the high-income countries. Last but not least, they often experience structural and political instability, which jeopardize the resilience of their health system [9, 20];
2) not related to health shocks, meant as the sudden onset of infectious diseases with widespread (but not necessarily global as pandemics) community diffusion, which can put hospital care under pressure and even at risk of disruption of clinical activity. We, thus, considered natural (e.g. earthquakes, floods, hurricanes, fires) as well as man-made (terrorism, biological/chemical threats, economic/financial crises, wars) disasters out of the scope of

[1] Search strings by database are reported in Appendix 2.

[2] Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia. Available at www.covidence.org.

[3] Notice that studies including both low-and-middle income and high-income countries, thereby identifying indicators adaptable to both contexts, were included.

[4] https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/WESP2022_ANNEX.pdf

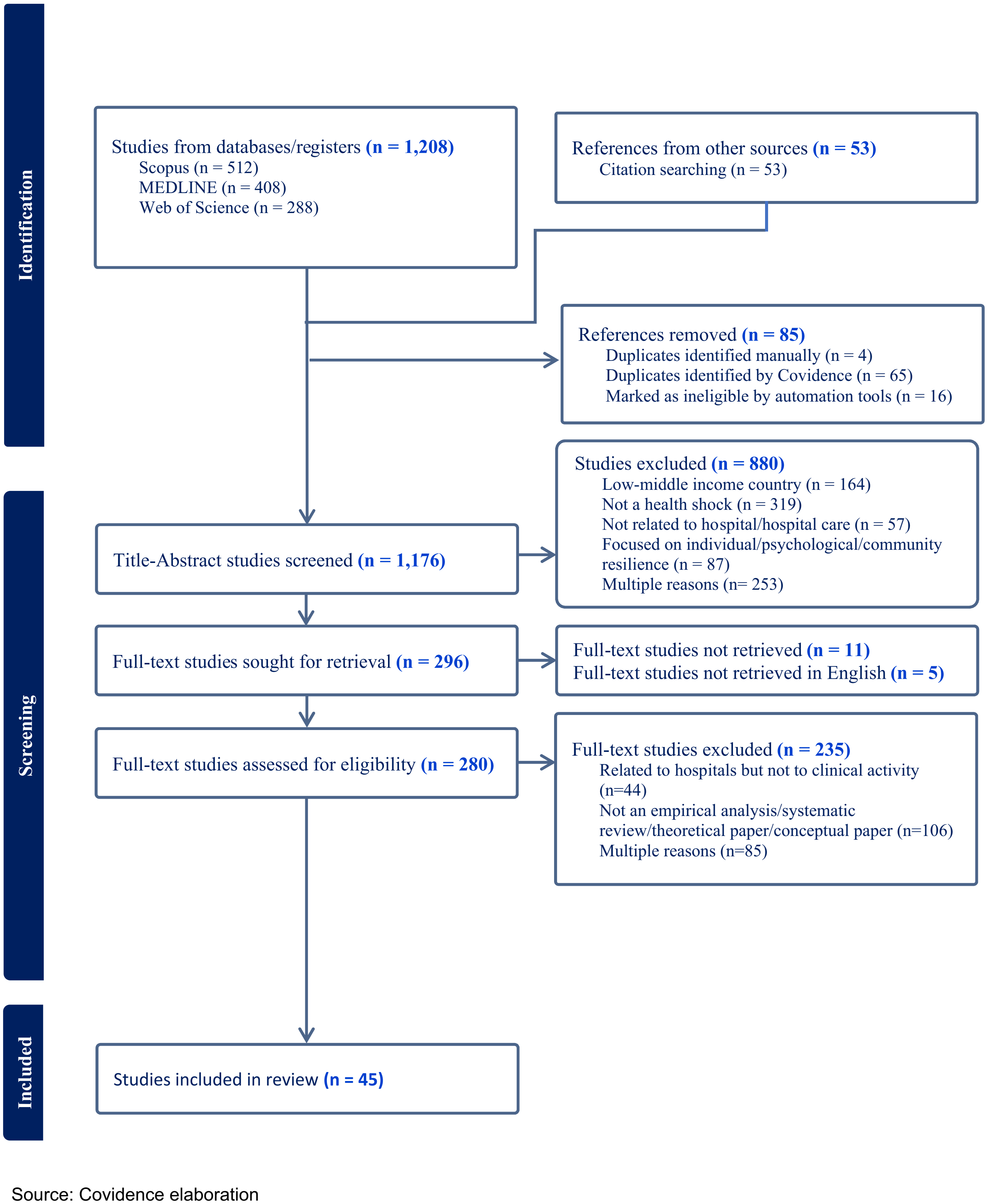

Fig. 1 PRISMA flow chart of the systematic review. Source: Covidence elaboration

the current review.[5] Furthermore, we focused on health disturbances that are sudden, extreme and unknown (although they can, to some extent, be anticipated) and not on health events that are known and chronic, such as those related to population aging, or on responses to the everyday management of health systems;

3) not related to hospital or hospital care. Although the resilience of other health sectors, such as public health, primary care, and long-term care, undoubtedly influenced hospital functionality during a shock through financial, managerial, and logistical support from ministries and government, our analysis specifically focuses on hospitals. Specifically, only studies addressing the impact of health shocks on hospital clinical activity were considered for eligibility. While primary care is usually seen as responsible for public health functions, recent studies show that hospitals also play a key role in ensuring essential public health services. For this reason, we focused only on hospitals and left out other sectors like public health, primary care, and long-term care. Hospitals are seen as the backbone of health systems during emergencies, not just at the start of a pandemic but also during recovery, where keeping them functional is crucial [21]. Additionally, hospitals faced the biggest financial challenges during Covid-19, with higher costs from hospitalizations, lost revenue due to cancelled services, responsibilities for purchasing personal protective equipment, and the need to provide psychological support for their workers[6];
4) focused on individual, psychological or community resilience. Following Tan et al. [19], we focused on hospital resilience at a higher hierarchical level than the micro one (referring to individual).[7] Therefore, we exclude articles dealing with resilience of people, patients, or hospital personnel [22].

Overall, 880 studies were excluded. Most of the papers removed after title and abstract reading discussed hospital resilience in the context of natural disasters, economic crises or conflicts (319 studies). Other studies were ineligible because they concerned low-middle income countries (164 studies), focused on individual/psychological/community resilience (87 studies), were not related to hospital care (57 studies) or due to multiple reasons (253 studies).

As a second screening step, full-text formats from the 296 relevant studies were retrieved and carefully read for inclusion by two independent reviewers', with again a third reviewer introduced only in case of disagreement. Of these, 11 full texts were not found and other 5 full texts were not retrieved because they were not written in English. Hence, 280 full-text studies were assessed for eligibility according to the following additional exclusion criteria:

1) Related to hospitals but not to clinical activity. Therefore, we exclude studies which, although analyzing resilience within the hospital setting, do not directly deal with clinical activity but, with non-clinical services and facilities (e.g., hospital energy resilience);
2) not an empirical analysis/systematic review/theoretical paper/conceptual paper; we, thus, exclude qualitative or descriptive studies.

Having removed papers lacking any quantitative analysis (106 papers) or not focusing on hospital clinical resilience (44 papers) or being excluded for multiple reasons (85 papers), the final paper list is made up of 45 items. These studies were then read by independent reviewers to extract the results relevant to the review question while minimizing bias and other errors. In doing this, a form of PICO (Population, Intervention, Comparison intervention, and Outcome measures) mnemonic was employed, which is the most commonly used framework for structuring clinical questions in evidence-based practice [23].[8] Besides key findings, other details such as data source, study period, countries considered for the analysis, clinical areas, study design and metrics were recorded. All these characteristics were then synthesized in easy-to-read synoptic tables to enable comparisons (see afterwards). Finally, citation details of the included studies were also considered.

Basic summary of the sampled publications

In this Section, we analyze the content of the sampled publications.[9] Four groups were identified. Table 1 lists the included papers by group and methodological design. The

[5] Focusing exclusively on health shocks is aligned with the primary objective of the paper: to identify metrics, indicators, or methodologies that can be generalized across contexts and scenarios to assess hospital resilience. Including non-health shocks, such as natural disasters or wars, would not support the collection of indicators that are adaptable to all contexts. These types of shocks are more prevalent in low- and middle-income countries, which often exhibit unique characteristics, including limited financial and human resources, that would significantly influence resilience assessments.

[6] Additionally, hospitals are more comparable across high-income countries, whereas primary care systems differ substantially in their organization. This limits the generalizability of systematic review findings if broader sectors are included.

[7] Indicators related to people (e.g., patients, staff) fall outside the scope of this paper, as they are often influenced by subjective decisions and are therefore less generalizable.

[8] To ensure the reliability of the data-extraction process, the data-extraction form was pilot tested beforehand, data extractors were trained, having (at least) two people extracting data from each study and conduct an independent extraction before conferring with each other.

[9] A synoptic table which collects all the 45 reviewed papers, differentiating them by the specific method employed (e.g., cross-country analysis, forecasting model, machine learning, data envelopment analysis, before-and-after comparison, interrupted time series analysis) and the shock considered (e.g., airborne pandemic, non-airborne pandemic, and generally endemic and crowding events) is reported in Appendix 1.

Table 1 Content classification (n = 45)

Group 1: Resilience in specific clinical areas	Group 2: Resilience and input capacities	Group 3: Resilience indices	Group 4: Resilience forecasting models	Hybrid
Cross- sectional studies [24–26]	Cross- country studies [27–29]	Cross- country studies [30, 31]	Deterministic models [29, 32]	Efficiency analysis [33]*
Descriptive studies [34–38]	Descriptive study [39]	Risk assessment [40]	Dynamic model [41]	Event simulation [42]**
Prospective studies [32, 43–46]	Efficiency analysis [47]		Mixed methods [48]	
Retrospective studies [25, 49–59]	Retrospective study [60]		Predictive model [61]	
	Survey studies [62, 63]		Probabilistic model [64]	

*Between Resilience and input capacities group (group 2) and Resilience indices group (group 3). ** between Resilience indices group (group 3) and Resilience forecasting models group (group 4)

first group collects papers that investigate the impact of the shock on specific clinical areas (hereafter, 'Resilience in specific clinical areas' group). The second group refers to papers that generally assess hospital resilience by means of intensive care unit (ICU) bed and staff capacity (hereafter, 'Resilience and input capacities' group). The third group includes studies that specifically construct indicators, such as the capacity of reaction of health system and the capability of countries to stop and/or reduce the impact of future outbreaks (hereafter, 'Resilience indices' group). Finally, the last group considers papers based on forecasting models, which simulate alternative schedule and allocation procedures (hereafter, 'Resilience forecasting models' group).

Most of the papers fall into the Resilience in specific clinical areas group (25 papers, corresponding to approximately 56% of the final sample), followed by Resilience and input capacities group with 9 papers (about 20%), Resilience forecasting models group with 6 papers (13%) and Resilience indices group with 3 paper (7%). Additionally, 2 papers (4%) cannot be categorized into a single group (i.e., a paper lies midway between Resilience and input capacities group and Resilience indices group, another paper lies midway between Resilience indices group and Resilience forecasting models group) (hereafter, 'Hybrid'). Focusing on the study design, most of the papers included in the sample employ either prospective or retrospective analyses.

The date of publication of the papers included in this systematic review confirms that the interest in resilience and how to measure it has gained popularity in the last few years, especially after the outbreak of Covid-19. Specifically, looking at the full sample of papers screened by title and abstract (i.e., 1,176 papers), we observe a sudden upward trend in the number of publications starting in 2020 (blue histograms in Fig 2). Restricting the analysis to our

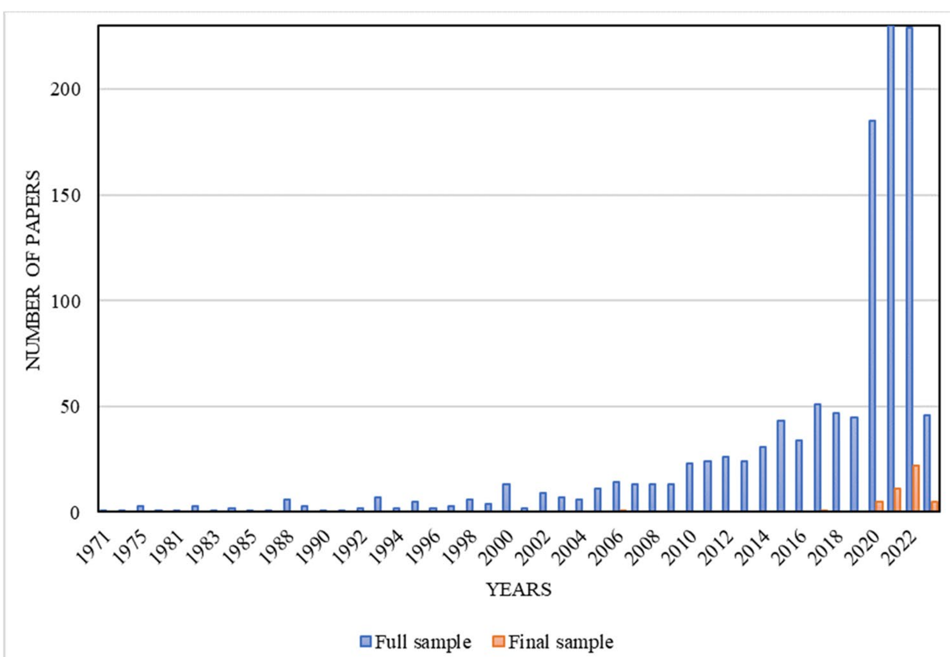

Fig. 2 Number of papers per year—full sample of papers screened by title-abstract (N = 1,176) and final sample (N = 45)

Table 2 Number of papers in the sample by journal's subject field

Type of journal	N. of papers
Journals with a focus on medicine in general	5 (11.1%)
Journal with a focus on specialties, clinical areas and specific diseases	25 (55.6%)
Journals with a focus on public health	3 (6.7%)
Journals with a focus on health economics and health policy	5 (11.1%)
Journals with a focus on environmental issues	3 (6.7%)
Other journals	4 (8.9%)
TOTAL	45 (100%)

Source: our elaboration on the SCOPUS database

Numbers in parentheses represent the percentage of papers in the sample

final sample (i.e., 45 papers), 73% of the papers have been published either in the year 2020 or in the year 2021 (orange histograms in Fig. 2).

Table 2 classifies the papers included in our final sample by the journal's subject field (e.g., medicine in general, specific clinical areas, public health, etc.). Overall, the 45 papers are published in 41 different journals, mostly (66.7%) in the medical area with a focus either on general medicine (4 journals) or on specific specialties/clinical areas/diseases (23 journals). Only three journals have published more than one paper of our final sample. Among these, Stroke is the journal that has published the highest number of studies (3 papers). Looking at the journals' scientific influence, 23 papers (51.1%) are published in journals that belong to the 25% of the journals with the highest 2022 SCImago Journal Rank (SJR).[10] The share of publications in either the first or the second quartile by SJR is 75.6% (34 papers).

Regarding the citation performance of the papers in the sample, this is strongly affected by the fact that most of them were published very recently. The total number of citations received by the 45 publications is 1,222, with an average of 27.2 citations per paper. The 10 most cited papers are listed in Table 3 together with the top 10 journals by (retrieved) article citations.

As a further step of our analysis, we use VOSviewer [66] to create the co-occurrence network of terms (i.e., adjectives and nouns) and display it on a two-dimensional map. From the titles and abstracts of the papers in our final sample, after setting binary counting and cleaning duplicates, 1,764 terms were extracted of which 129 occurred three or more times. Four clusters[11] emerged, which, based on the terms included, further validate our previous group classification. The four clusters are highlighted in different colours (Fig. 3): red cluster, fairly corresponding to what we previously indicated as the Resilience in specific clinical areas group, containing 23 terms; blue cluster, corresponding to the Resilience and input capacities group, containing 16 terms, among which "surge capacity", "demand", "response", "ICU" and "beds"; green cluster, corresponding to the Resilience indices group, with transverse terms not specific to other clusters and containing 18 terms among which "index", "preparedness", "effectiveness", "performance"; yellow cluster, corresponding to the Resilience forecasting models group, containing 13 terms among which "pattern", "improvement" and "previous year". The most cited terms were: "resilience" (12 occurrences), "country" (11 occurrences), "response" (10 occurrences), "index" (9 occurrences) and "surge capacity" (9 occurrences). Figure 4 shows all the terms directly connected with the largest node (according to the number of occurrences) in Fig. 3, that is, "resilience". As can be seen from Fig. 4, most of the links regarding the term"resilience"occur with the terms that are part of the green cluster, the one focused on indicators.

Review

In the following section we focus on the papers belonging to Resilience in specific clinical areas group, before moving to papers belonging to the other groups. In accordance

[10] SJR is a size-independent indicator of journals' scientific prestige that ranks scholarly journals based on citation weighting schemes and eigenvector centrality. Within SJR, citations are weighted by the prestige of a journal. Subject field, quality, and reputation of the journal have a direct effect on the value of a citation. For more information on Journal Metrics and the use of SJR, see: https://www.scimagojr.com.

[11] The clustering procedure implies that for each of the 129 terms, a relevance score was calculated [66]. This score facilitated the selection of the most relevant terms among these 129 terms, which corresponded to 70 terms. Each of these 70 terms was then assigned to one cluster based on a computer algorithm and used to create the co-occurrence map of terms displayed in Fig. 3. Each cluster has its own colour. When the colours are mixed, then the algorithm could not make clear distinctions between the clusters. The size of each node shows the number of occurrences of each term and links between the nodes show the relationship of terms. The width of the links depicts the power of terms based on co-occurrence.

Table 3 Most cited papers and journals in terms of total citations (TC) and average citations per year (TC/years since publication)

	TC in SCOPUS	TC/Year
Top 10 articles by citations		
Coccia [30]	156	78
Glasbey et al. [43]	155	51.6
McCabe et al. [39]	113	28.2
Jain et al. [64]	102	25.5
Toro et al. [34]	76	25.3
Soares et al. [49]	55	37.5
Lupu and Tigasanu [65]	52	26
Manley et al. [62]	52	2.9
Winkelmann et al. [63]	49	24.5
Romani et al. [32]	46	15.3
Top 10 journals by article citations		
Environmental research (1)	156	78
The Lancet Oncology (1)	155	51.6
BMC Medicine (1)	113	28.2
The Journal of Bone and Joint Surgery (1)	102	25.5
Health Policy (2)	83	20.7
European Journal of Ophthalmology (1)	76	25.3
Stroke (3)	71	7.1
Annals of Emergency Medicine (1)	55	37.5
Health Economic Review (1)	52	26
Disaster Management & Response (1)	52	2.9

Source: our elaboration on SCOPUS database (retrieved February 26th, 2024)

Numbers in parentheses represent the papers in the sample. Years since publication are computed up to 2024

with the data extraction procedure previously described, for each of the paper, regardless of the reference group, we indicate the data source, the period of observation, the country where the analysis has been conducted, the concerned clinical area and the metrics employed (Table 4, for the Resilience in specific clinical areas group and Table 5 for the other groups). Finally, we briefly summarize the main results obtained (Table 6 for the Resilience in specific clinical areas group and Table 7 for the other groups).

Resilience in specific clinical areas

To conduct the analysis, in most of the 25 studies that focus on the assessment of specific clinical areas administrative data, such as those obtained from hospital discharge plans [35, 68] or clinical records (e.g., patients registry), is used [25, 46, 52, 53, 67, 69]. Further data are taken from national databases [35, 37, 49, 58]. Finally, a minority of studies collect data online, resort to press sources [43] or conduct surveys or interviews with patients [26].

As far as the period of analysis is concerned, scholars generally compare the selected metrics before and after the pandemic. First, a specific time interval is selected, such as the quarter corresponding to the first wave of the pandemic (i.e., February-May 2020). Second, the chosen time frame is compared to the same period of the previous year (i.e., 2019) [25, 67]. Alternatively, data referred to the pandemic period are matched against the annual or a two/three-year pre-pandemic average [44].

Unlike studies belonging to the other groups, many studies in Resilience in specific clinical areas group are nationally based [24, 54, 68], and some of them are restricted to a specific local area (e.g., a specific province/region) [52, 53, 58]. Few of them are conducted across multiple global regions [43, 67]. Most of the nationally based studies concern European countries, despite a restricted number of papers refer to the United States [24, 49, 57].

In the group considered, the impact of Covid-19 on clinical activity is assessed by looking at specific medical areas. A wide range of studies focuses on cerebrovascular diseases such as stroke, ST- segment elevation myocardial infarction and transient ischemic attack [44, 46, 67]. Similarly, cardiovascular diseases such as acute myocardial infarctions are largely covered [35, 36]. Further disorders commonly said to be affected by Covid-19 that are worth investigating concern cerebral system such Parkinson and dementia [58, 68]. However, the pathologies that seem to be mostly assessed in the context of the pandemic are HIV and cancers [51, 53, 54, 57]. With reference to the former, due to the lockdown restrictions and the related social distancing measures, in several countries there has been a drastic reduction in the spread of sexually transmitted infections such as HIV, which has made it possible to save resources intended to the management of such venereal diseases. As far as the latter is concerned, while some studies deal with different cancer types [43, 51], one study specifically focuses on female breast, colorectal and non-small cell lung cancer [54]. Finally, a restricted space is reserved to the effects of Covid-19 on diabetes [52], otorhinolaryngology [56], spine surgeries [69], urological surgery [37], eye care [34, 38], gout [26], opioid overdose [49] and delivery [24].

Moving to the metrics employed in Resilience in specific clinical areas studies, these tend in most cases to measure the hospital's ability to cope with the shock while preserving clinical activity either with the same resources (absorptive capacity) or thanks to organizational changes (adaptive capacity).

A relevant share of papers uses waiting times as a measure of resilience of the specific medical area, such as onset-to-admission-time (e.g., for stroke), admission-to-treatment-time [67], diagnosis-to-management-time [45, 53, 67]. Other recurring proxies for the capacity of

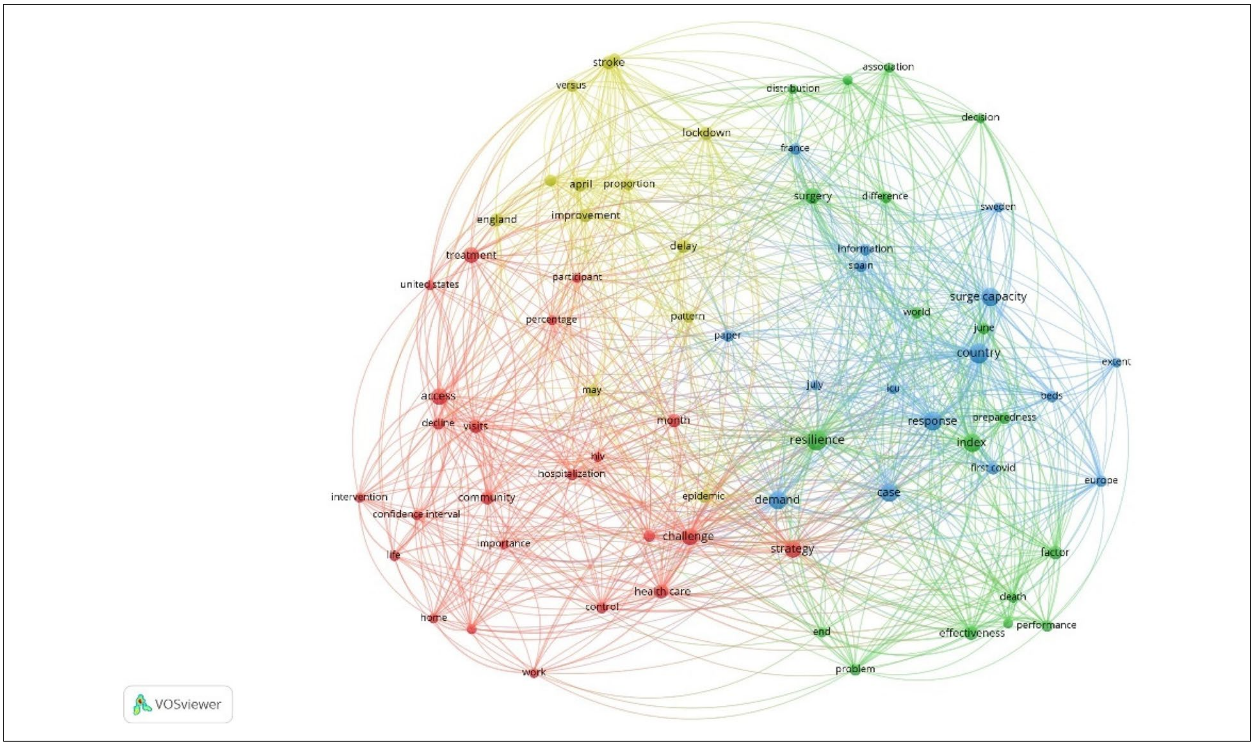

Fig. 3 Co-occurrence map of terms in titles and abstracts

mitigating the effects of the health shock are the number of interventions, treatments, procedures, visits or screening performed (e.g., mitral clip procedures, endovascular therapies, surgeries, injections, cancer screenings) [34, 35, 37, 51, 55, 58, 69].

The trend of new diagnoses (e.g., cancer) is also crucial for assessing the capacity of a system to withstand a shock since it captures the speed of the health service in detecting the onset of a new pathology [25, 53, 57], through tests, consultations or referrals, which could be instead postponed with the outbreak of the pandemic. Further indicators which deserve to be mentioned are quality metrics (length of stay, stroke unit within 4 h of arrival at hospital, brain imaging within 1 h) [44, 45], non-operation rates [43], emergency department admissions, and hospitalizations [68]. Finally, mortality rate is certainly among the most widely employed index in the literature, not only for evaluating the spread of the epidemic (i.e., computing Covid-19 related deaths), but also to measure the indirect impact[12] of Covid-19 on other pathologies, which may be overlooked under an emergency (e.g., cardio-cerebrovascular disease mortality, stroke, cancer) [35].

[12] Notice that by indirect impact we refer to both pathologies which deteriorate due to SARS-CoV-2 infection but also to diseases which are neglected because capacity and treatment are drained by the pandemic.

Finally, focusing on the results, most of the papers find that Covid-19 pandemic has a destructive impact on many indicators. For example, a significant reduction in surgery volumes is documented [34, 37, 43], since many departments—such as ophthalmology, urology, oncology, orthopedics -, were forced to postpone planned operations to save resources allocated to the pandemic management. Huge reductions in the number of treatments or therapies (e.g., reperfusion therapy, physiotherapy to peritoneal dialysis patients, fibrinolytic therapy, endovascular therapy) [36, 55, 58, 67], screenings [53] and diagnoses [51, 54] are similarly registered.

However, keeping in mind the definition of resilience provided initially, few studies focus on the last dimension of shock management, namely the recovery/transformative capacity, proving that most services (e.g., home care visits, physicians visits, hospital admissions, cancer screenings, HIV tests, outpatient visits, outpatient exams) returned to their pre-shock levels by the end of the first-wave [51, 57, 58, 68]. Similarly, the rate of out-of-hospital deliveries, which increased during the first wave, returned to historic levels as of August 2020 [24].

Many performance indicators show a deterioration during the pandemic (e.g., onset-to-admission, admission-to-treatment time, admission-to-image, image-to-treatment time) [43, 45, 46], despite very few studies find no significant difference before and after Covid-19 [67]. Mortality

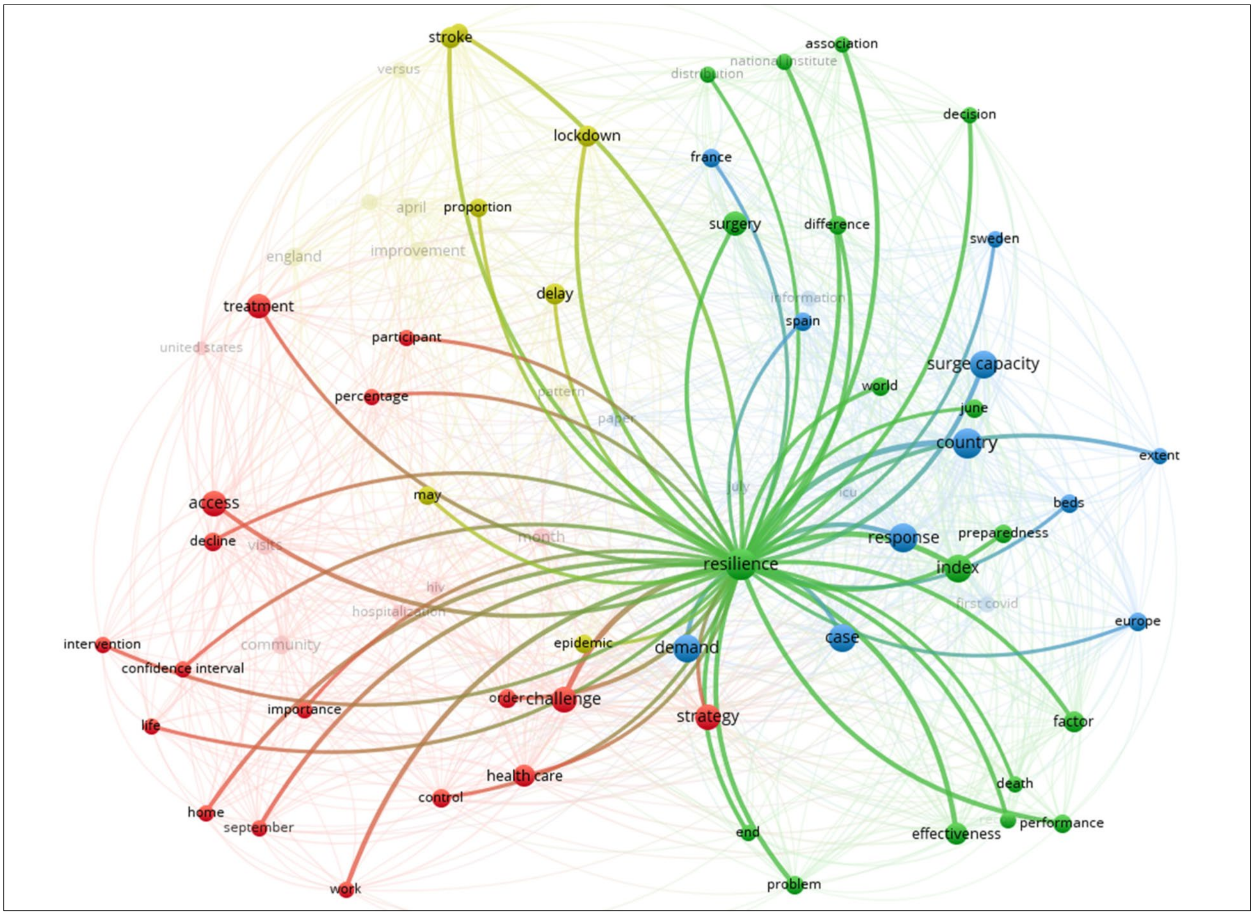

Fig. 4 Network visualization of terms connected with “resilience”

rates increase for some pathologies such as Parkinson and dementia and cardiovascular diseases [35, 68]. Additionally, an increased use of telemedicine is reported [25, 68]. Moreover, thanks to the adoption of stricter hygienic measures and the limitations in the number of visits during Covid-19, post-operative infections declined at least for spine surgery [69].

Finally, even though Covid-19 is said to primarily affect the healthcare system from a supply perspective, many studies also concentrate on patients’ behaviour. First, Covid-19 also affects socio-economic conditions, leading individuals to suicidal ideation as reported by Caldas et al. [50]. Second, given the risk of SARS-Covid-19 infection, patients delayed access to hospital care [70, 71], resulting in missing visits [25], reduction in check-ups and health service use [47, 48], increase in onset-to-arrival-time [46], decrease in admissions to ED [52]. Despite postponing intended routine may lead to health consequences for individuals, especially those suffering from chronic conditions, from a supply of care perspective, reduced access to hospital care, which avoids overcrowding, increases the amount of patients with an optimal pathway [54] as well as the number of adequate visits[13] [56] and improves quality indicators for stroke conditions, given the reduction in stroke admissions [44].

Resilience and input capacities, resilience indices and resilience forecasting models studies

Cross-country studies belonging to Resilience and input capacities, Resilience indices and Resilience forecasting models groups resort to international databases such as OECD statistics [27], Our World in Data [30], Health System Respond Monitoring [63], World Bank [33], and World Health Organization [65] to carry out the analysis. Nationally-based studies rely, instead, on administrative data [31],

[13] The emergency suitability protocol of the Complexo Hospitalario Universitario de A Coruña, where the study in question was conducted, establishes the appropriateness of a visit according to 5 factors: clinical severity of the patient, intensity of the treatment administered, need for urgent diagnostic tests, outcome of the consultation to Emergencies and the existence of particular situations justifying the adequacy of spontaneous visits [56].

Table 4 Resilience in specific clinical areas studies

Authors	Data Source	Period	Country	Clinical area	Metrics
Altersberger et al. [67]	Thrombolysis in Ischemic Stroke Patients registry	February-April (2019–2020)	Switzerland, Germany, Italy, France, Finland, Greece, Israel, Serbia, Sweden, The Netherlands	Acute ischemic stroke treated with reperfusion therapies	Onset-to-admission time, admission-to-treatment time, National Institutes of Health Stroke Scale score 24 h after admission, the occurrence of symptomatic intracranial hemorrhage
Bronskill et al. [68]	Canadian Institute for Health Information Discharge Abstract Database, National Ambulatory Care Reporting System, Ontario Health Insurance Plan Claims Database, Health Shared Services Ontario Home Care Database, Continuing Care Reporting System Long-Term Care Database	March-September (2019–2020)	Canada (Ontario)	Dementia and Parkinson disease	Weekly rates of all-cause health service use (emergency department visits not resulting in a hospitalization, hospitalizations, e.g., admissions, discharges, and delayed discharges, physician visits, home care visits, and nursing home admissions) and mortality
Caldarola et al. [35]	ISTAT, hospital discharge plan	n.a	Italy	Cardiovascular diseases	Cardio-cerebrovascular disease mortality (heart failure, PCTA, infarction, other), percutaneous transluminal coronary angioplasty, number of percutaneous transcatheter implants of aortic valve prosthesis, number of mitralic clip procedures, follow-up of patients with coronary syndrome, heart failure, atrial fibrillation treated with anticoagulants, or with cardiological devices diseases
Caldas et al. [50]	n.a	October-December (2019–2020)	Portugal	Liason psychiatric	Hospitalisation length before CR (collaboration request), number of psychiatric consultations of LP during hospitalisation and intervention performed (formal psychiatric diagnosis and need for therapeutic adjustment)

Table 4 (continued)

Authors	Data Source	Period	Country	Clinical area	Metrics
Carroll et al. [51]	health information exchange	January 2019-December 2020	USA (North Carolina)	Cancer	Number of screening and diagnoses for: breast cervical colorectal leukemia lung and bronchus prostate
Cash et al. [24]	National EMS Information System Public Release Research Datasets	January 2019-December 2020	USA	Delivery	Weekly rate of emergency medical services -attended out-of-hospital deliveries per 100,000 EMS emergency activations
Chandok et al. [52]	NHS Digital, Quality and Outcomes Framework data, NHS Ealing Clinical Commissioning Group	January 2020-March 2021	England (Ealing)	Diabetes	Key Care Processes (KCPs) for Diabetes, avoided admissions for people with diabetes aged 17 and over, diabetes-related emergency admissions (cerebrovascular accident, diabetes mellitus, diabetic ketoacidosis, hypoglycaemia, myocardial infarction, amputations)
Douiri et al. [44]	Sentinel Stroke National Audit Programme	October 2019- April 2020 and equivalent periods in the 3 prior years	UK	Acute stroke (ischemic, primary intracerebral hemorrhage or undetermined type)	Onset in or out of hospital, time from onset to admission, pre-stroke modified Rankin Scale score, National Institutes of Health Stroke Scale score, interventions and care quality metrics (stroke unit within 4 h of arrival at hospital, brain imaging within 1 h etc.), all-cause inpatient mortality within 7 days of admission and modified Rankin Scale score at discharge from hospital

Table 4 (continued)

Authors	Data Source	Period	Country	Clinical area	Metrics
El Moussaoui et al. [53]	Administrative data from Liege University Hospital	January 2019-December 2020	Belgium (Liege)	HIV	Number of new HIV diagnoses, number of out-patient follow-up visits to a specialist in infectious diseases, number of psychology or sexology consultations, number of patients who underwent screening for comorbidities and coinfections, number of blood CD4 þ T-cells absolute count analyses and HIV plasma viral load (VL) assays performed, HIV plasma VL value, delay between the diagnosis and the management
Glasbey et al. [43]	National policy, media, and press sources, data collected online	January-August 2020	Australia, Austria, Barbados, Belgium, Canada, Egypt, Chile, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hong Kong, Hungary, Ireland, Italy, Japan, Kuwait, Netherlands, Oman, Portugal, Saudi Arabia, Singapore, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, UK, USA, Argentina, Azerbaijan, Botswana, Brazil, Colombia, Guatemala, Jordan, Libya, Malaysia, Mexico, Peru, Romania, Russia, Serbia, South Africa, Sri Lanka, Turkey, Ghana, India, Indonesia, Morocco, Nigeria, Pakistan, Philippines, Reunion Sudan, Syria, Uganda, Yemen	Cancer surgery (gastric, head and neck, thoracic., liver, pancreatic, prostate, bladder, renal and upper urinary tract urothelial, gynaecological, breast, soft-tissue sarcoma, bony sarcoma, and intracranial malignancies)	Non-operation rate, resection margin status for those selected for surgery, resectable disease at the time of surgery, preoperative cancer complication requiring emergency surgery, 30-day postoperative SARS-CoV-2 infection rate, 30-day post-operative mortality rate, new detection of metastatic disease up to a maximum of 30 days after surgery

Table 4 (continued)

Authors	Data Source	Period	Country	Clinical area	Metrics
Greene et al. [54]	Cancer Network Information System Cymru	January 2019-December 2020	Wales	Female breast, colorectal and non-small cell lung cancers	Annual and monthly incident case counts, stage at diagnosis and annual and quarterly healthcare pathway to diagnosis (screening, general practitioner urgent suspected cancer referral, emergency presentation/admission, in-patient referral, out-patient referral)
Guddeti et al. [36]	n.a	n.a	USA, UK	Acute myocardial infarction	Segment elevation myocardial infarction activations
Hajdu et al. [55]	n.a	November 2019-April 2020	Switzerland, Italy, France, Spain, Portugal, Germany, Canada, USA	Endovascular therapy for patients with acute ischemic stroke	Mean number of EVTs performed, mean stroke onset-to-groin puncture time interval per hospital and per 2-week interval
Herranz-Larrañeta et al. [56]	Servizo Galego de Saúde	March–May (2019–2020)	Spain	Otorhinolaryngology	Origin of the patient (referred after evaluation by PC physician or another emergency physician, or on their own initiative), outcome of the consultation (discharge or admission, referral to the hospital emergency department, follow-up in outpatient) and the adequacy of the consultation to the emergency department according to the Hospital Emergency Suitability Protocol (HESP) (clinical severity of the patient, intensity of the treatment administered, need for urgent diagnostic tests, outcome of the consultation to Emergencies and the existence of particular situations that justify the adequacy of spontaneous visits)

Table 4 (continued)

Authors	Data Source	Period	Country	Clinical area	Metrics
Jankovic et al. [69]	Medical records	January 2019- June 2021	Germany (Mainz)	Spine surgeries	Number of spinal operations, duration of the operation, postoperative complications, urinary tract infection (UTI), new SARS-CoV2 infection, pneumonia, deep venous thrombosis, pulmonary embolism (PE), and wound infection, length of stay in days
Lesaine et al. [45]	Hospital information system, electronic care records and ex- tracted or collected retrospectively by clinical research assistants	January 2019-August 2020	France	Stroke and ST- segment elevation myocardial infarction	Stroke clinical severity, stroke type (ischaemic/haemorrhagic), calls to emergency services, first medical contact and symptom-to-care time, intervals between key management steps (stroke, EU admission- to-imaging time; STEMI, FMC-to-procedure time), prehospital and hospital pathways, mode of transport to the EU, orientation to stroke unit or cathlab and treatment (stroke, first imaging type, IV thrombolysis (IVT) in ischaemic stroke, mechanical thrombectomy in ischaemic stroke; STEMI, fibrinolysis, percutaneous coronary intervention, coronary angiography alone)
Niu et al. [57]	Programmatic database of memorial healthcare system	July 2018-March 2021	USA (South Florida)	HIV	Number of HIV tests done per month
Quiros-Roldan et al. [25]	Administrative data, electronic and paper clinical records	October–November 2019, March–April 2020	Italy (Brescia)	HIV	New HIV diagnosis, number of medical visits in HIV out-patients clinic, dispensation of antiretroviral medications and hospitalizations of people with HIV

Table 4 (continued)

Authors	Data Source	Period	Country	Clinical area	Metrics
Robert et al. [37]	National database	2010–2020	France	Urological surgery	Number of urology surgery procedures (rostate cancer, partial and radical nephrectomy in kidney cancer, transurethral resection in bladder cancer, radical cystectomy, benign prostatic hyperplasia, suburethral slings for female urinary incontinence, and endoscopic and percutaneous procedures for kidney calculus)
Rydell et al. [46]	Riksstroke national register, hospital records and hospital registrer at Danderyd Hospital	March-August (2019–2020)	Sweden	Stroke and transient ischemic attack	Number of stroke patients admitted, time for onset of stroke symptoms, time to arrival at hospital, door-to-needle time to intravenous thrombolysis, stroke severity at admission, in-hospital mortality rate, positive test for COVID-19 infection, planned diagnostic stroke work-up, and out-clinic follow-up
Singh and Edwards [26]	survey	November 2020 and June 2021	USA	Gout	Use of gout medications including urate-lowering therapy, difficulty with gout care, health care access, gout flares, gout-specific, psychological distress, resilience, medication adherence
Soares et al. [49]	National Center for Health Statistics Mortality Files	January 2018-December 2020	USA (Alabama, Colorado, Connecticut, North Carolina, Massachusetts, and Rhode Island)	Nonfatal opioid overdose	Weekly counts of ED visits with 1 or more International Classification of Disease-10 diagnosis codes associated with an opioid overdose
Toro et al. [34]	n.a	n.a	Poland, France, Ireland, Turkey, Italy, Russia, Portugal, Spain, Finland	eye care	Number of ophthalmological procedures (phacoemulsification, glaucoma-surgery, vitrectomy, intravitreal injection, keratoplasty)

Table 4 (continued)

Authors	Data Source	Period	Country	Clinical area	Metrics
Vignatelli et al. [58]	Unità Operativa Epidemiologia e Statistica	July 2019-September 2020	Italy (Bologna)	Parkinson's disease, atypical parkinsonism, and vascular parkinsonism	Number of outpatient visit, number of neurologic outpatient visit, number of outpatient physical therapy visit or activity, number of test (lab/diagnostic/neuroradiologic), non-urgent hospital admission, overall prescription of any drug, and drugs specific for PD, urgent hospital admission, hospital admissions for major injuries, infections, gastro-intestinal events, thromboembolic events, psychiatric events, hypotension/syncope, acute cardiac events, and acute cerebrovascular events
Weng et al. [38]	n.a	n.a	n.a	Intravitreal injection (IVI) of antivascular endothelial growth factors or steroids	IVI deliveries

Table 5 Resilience and input capacities, Resilience indices and Resilience forecasting models studies

Authors	Data source	Period	Country	Metrics	Group
Berger et al. [27]	Ministries of Health, national research and public health institutes, Our World in Data, OECD/European Union, Health System Response Monitor	February–March 2020	Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Sweden, UK	Hospital and ICU bed capacities prior to COVID-19, ICU surge capacity during the first wave of COVID-19, cumulative days of hospitalization and cumulative days of ICU stay, mean numbers of hospital days and ICU days per infected case, proportion of cumulative patients infected with SARS-CoV-2 requiring hospital treatment and ICU treatment	Resilience in specific clinical areas
Cacace et al. [28]	Questionnaire, OECD Health Statistics, Central Bureau of Statistics, interviews	January-July 2020	Denmark, Germany, Israel, Spain, Sweden	Number of beds (hospital acute care beds per 1000 population, intensive care beds per 100,000 population, ICU for pediatric/neonatal, number of pulmonary units), occupation rates and staff counts (physicians' density per 1000 population, nurse-to-bed ratio, professional nurses and midwives, density per 1000 population, physicians per 1000 inpatient cases, professional nurses and midwives per 1000 inpatient cases)	Resilience in specific clinical areas
Coccia [30]	Our World in Data, European Centre for Disease Prevention and Control, Johns Hopkins Center for System Science and Engineering	February 2020-February 2021	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, UK	Index r: average mortality rate is given by (number of deaths divided by population of country) per 100000 inhabitants, daily hospital occupancy per 100000 inhabitants, intensive Care Units (ICUs) occupancy per 100000 inhabitants Index p: doses of vaccines administered per 100000 inhabitants at February–March 2021, total vaccinates per 100000 inhabitants at February–March 2021 between countries	Resilience indices
D'Aeth et al. [29]	Hospital Episode Statistics, NHS digital	2015-April 2020	England	Available resources, current allocation of patients (waiting versus in-hospital patients, in critical care versus general and acute care, and so on), transition matrices (the probabilities of endogenous transfers of patients between severity groups)	Resilience forecasting models
Davis et al. [61]	Hospital Medical records	May 2016	USA (Virginia)	National Emergency Department Overcrowding Scale (current number of ED patients, number of ED beds, number of inpatient beds, the last door-to-bed time, the longest admit time, and number of critical care patients in the ED), number of ED beds in use by hour, staffing schedule, timestamps (starting with arrival time to ED, time to ED bed, time to physician disposition, and time to floor bed)	Resilience forecasting models

Table 5 (Continued)

Authors	Data source	Period	Country	Metrics	Group
Duarte et al. [48]	Medway Foundation Trust	January-October 2020	UK	Patients in department (hourly average number of patients waiting to be seen in the ED), patient attendances (hourly total number of patients with major injuries attending the ED), unallocated patients with DTA (number of patients that have been attended, not discharged, but waiting to be admitted to the hospital, thus occupying resources) medically fit for discharge (total number of patients who have attended, and do not need further treatment)	Resilience forecasting models
Glasbey et al. [31]	International consultation, hospital administrative data	June–August 2019–2021	Afghanistan, Albania, Algeria, Argentina, Aruba, Australia, Austria, Azerbaijan, Bahamas, Bahrain, Bangladesh, Barbados, Belarus, Belgium, Benin, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria,Cambodia, Cameroon, Canada, Chile, China, Colombia, Croatia, Cyprus, Czechia, Denmark, Dominican Republic, Ecuador, Egypt, Estonia, Ethiopia, Finland, France, Georgia, Germany, Ghana, Greece, Guatemala, Hong Kong, Hungary, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Japan, Jordan, Kazakhstan, Kenya, Kuwait, Latvia, Lebanon, Libya, Lithuania, Madagascar, Malawi, Malaysia, Malta, Mexico, Moldova, Mongolia, Morocco, Nepal, Netherlands, New Zealand, Nicaragua, Niger, Nigeria, Norway, Oman, Pakistan, Palestine, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, North Macedonia, Romania, Russia, Rwanda, Saudi Arabia, Senegal, Serbia, Singapore, Slovakia, Slovenia, Somalia, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syrian Arab Republic, Taiwan, Thailand, Trinidad and Tobago, Tunisia, Turkey, Uganda, Ukraine, United Arab Emirates, UK, USA, Uruguay, Venezuela, Yemen, Zambia, Zimbabwe	Surgical preparedness indicator: planned surgical volume ratio (ratio of the observed surgical volume over a 1-month assessment period in 2021, against the expected surgical volume based on hospital administrative data from the same period in 2019)	Resilience indices

Table 5 (Continued)

Authors	Data source	Period	Country	Metrics	Group
Jain et al. [64]	National Inpatient Sample (NIS)	1993–2022	USA	Sum of total knee arthroplasty, total hip arthroplasty, cervical or thoracolumbar spinal fusion surgical procedures performed in a given month	Resilience forecasting models
Kuzior et al. [33]	World Bank	2015–2019	Cuba, Belgium, Canada, China, Iceland, Austria, Australia, India, UK, Czech Republic, Italy, Portugal, Norway, Switzerland, Thailand, Ukraine, Spain, France, Ireland, Germany, New Zealand	Physicians, nurses and midwives per 1000 people, labor force, total; hospital beds per 1000 people); level of mortality from various causes (mortality from CVD, cancer, diabetes or CRD between exact ages 30 and 70, in %, mortality rate, infants, per 1000 live births; mortality rate, under-5, per 1000 people; lifetime risk of maternal death, cause of death, by communicable diseases and maternal, prenatal and nutrition conditions, in % of total, etc.). Index of resistance to the pandemic: number of officially registered persons infected with COVID-19 in country j on 2 October 2022—number of officially registered persons who died because of the COVID virus	Hybrid
Lupu and Tiganasu [65]	Worldometer, World Health Organization, World Bank	January-December 2020 Covid-19 data 2019 health indicators	Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Norway, UK, Iceland, Switzerland	COVID-19 cases per 1 million population, physicians, nurses and midwives (per 1000 people), hospital beds (per 1000 population), COVID-19 deaths, Comorbidities Probability (%) of dying between age 30 and exact age 70 from any of cardiovascular disease, cancer, diabetes, or chronic respiratory disease	Resilience in specific clinical areas
Manley et al. [62]	Survey	n.a	USA	Number of patients that would overwhelm the ED resources, use of hospital disaster plans, training and preparedness to various events	Resilience in specific clinical areas
McCabe et al. [39]	National Health Service (NHS)	January – June 2020	England	Beds, nurses, junior doctors, senior doctors, ventilators (data are disaggregated by critical care resources, and general and acute resources)	Resilience in specific clinical areas
Muselli et al. [59]	Local Health Unit in Italian database	March–May 2019–2020	Italy (Abruzzo)	ED admissions (according to the triage code), length of stay, ratio between the non-urgent visits or subjectively perceived treatment urgency (white and green codes) and the non-deferrable urgency (red code), ratio between the number of hospitalizations and the red codes	Resilience in specific clinical areas

Table 5 (Continued)

Authors	Data source	Period	Country	Metrics	Group
Nunes and Ferreira [47]	Official database maintained by the central administration of health systems	January 2017-May 2021	Portugal	Number of days spent in the hospital wards, beds used in all hospital wards, number of days all admitted patients stay in the hospital wards waiting for major scheduled surgery, number of hours worked by all medical doctors and nurses, number of patients (both inpatients and outpatients) seen in the hospital, adjusted for their complexity and severity, number of registers on the surgery waiting list within the legally defined time, number of first medical appointments within the legally defined time, number of hip surgeries in the first 48 h after fracture, number of inpatients without adverse events, number of avoidable bloodstream infections, number of avoidable postoperative pulmonary embolisms, number of septicemia cases, number of delayed first medical appointments, number of registers on surgery waiting list beyond the legally defined time, number of readmitted cases after 30 days of inpatient discharge, number of hip surgeries beyond 48 h after fracture, number of avoidable bedsore cases	Resilience in specific clinical areas
Riccardo et al. [40]	Italian national institute of health	May 2020- September 2021	Italy	Resilience indicator: number of staff dedicated to contact tracing in each local health unit, number of staff dedicated in each unit to the activities for the collection and dispatch of clinical samples to the reference laboratories and monitoring of cases and close contacts placed in quarantine and in isolation, number of confirmed cases in the region for which an epidemiological investigation has been carried out, with the search for close and total contacts of new confirmed cases	Resilience indices
Romani et al. [32]	Istituto Superiore di Sanità, Center for Systems Science and Engineering at Johns Hopkins University, Istituto Nazionale di Statistica, Dipartimento della Protezione Civile, Modena Health Agency	February–March 2020	Italy (Modena)	ICU bed occupancy, COVID-19 diagnostic tests	Resilience forecasting models
Trentini et al. [60]	n.a	February-July 2020	Italy (Lombardy)	Daily number of intensive care unit beds occupied, duration of time between hospitalization and ICU admission, clinical outcome (i.e., recovery or death)	Resilience in specific clinical areas

Table 5 (Continued)

Authors	Data source	Period	Country	Metrics	Group
Trucco et al. [42]	ED information system, in-field visits and meetings with the medical officer responsible for the PEMAF (Piano di Emergenza per il Massiccio Afflusso di Feriti)	n.a	Italy (Lombardy)	Weighted Waiting Time Index: weighted average of the waiting time of the last patient in queue for each patient class. Hospital resilience under different resource allocation strategies or the baseline. Hospital resilience improvement number of patients treated in the ED, number of green code patients, number of yellow code patients, number of red code patients	Hybrid
Wang et al. [41]	n.a	n.a	n.a	Number of available hospital beds per 10,000 population, number of infected cases, hospital bed-population ratio	Resilience forecasting models
Winkelmann et al. [63]	Health System Response Monitor (HSRM)	March-August 2020	Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Croatia, Cyprus, Denmark, Estonia, Finland, France, Georgia, Germany, Hungary, Iceland, Ireland, Israel, Italy, Kyrgyzstan, Latvia, Lithuania, Luxembourg, Malta, Monaco, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, UK (England)	Reorientation of hospital departments/Creation of ICU, intermediate and acute care beds for COVID-19 patients, Designation of hospitals to treat COVID-19 patients, Creation of transition centres for recovery and/or quarantine, Use of private hospitals, Creation of new COVID-19 temporary/military field hospitals, Inter-hospital transport of COVID-19 patients to adjust for needs in local/national capacity, Use/set-up monitoring systems of bed capacity, Increase supply of personal protective and medical equipment, Repurpose and redeployment of existing health workforce	Resilience in specific clinical areas

hospital records [61], and national datasets [29, 39, 40]. Additionally, questionnaires and interviews are employed to collect data, albeit rarely (see [28] for a cross-country analysis, and [42, 62] for nationally-based studies).

A large proportion of papers from these groups almost exclusively focus on Covid-19 times, covering either the first wave only (February-August 2020) [27, 60, 63], or the overall pandemic period until the third wave (January-May 2021) [30, 40]. Between and after shock comparisons are also conducted [29, 31, 33, 39, 47, 59]. Finally, few papers do not deal specifically with Covid-19, but generally refer to crowding events or mass casualty incidents [41, 61, 62], although some of them propose linear programming frameworks that can be easily adopted in the context of a pandemic [31, 42].

Many studies present large-scale country-level analyses [30, 31, 33, 63, 65], comparing up to 119 countries [31]. A residual part of scholars limits their research to a specific territory (e.g., Portugal, UK, USA) [29, 47, 48, 61]. Finally, special attention is devoted to Italy [32, 40, 42, 59, 60], since it is considered one of the countries most affected by Covid-19 as measured by the number of deaths.

Focusing on the metrics adopted, as far as studies pertaining to Resilience and input capacities group are concerned, resources endowment is generally used to quantitatively measure hospital resilience in terms of either absorptive or adaptive capacity. In fact, Covid-19 or, more generally, any other health shock creates a sudden increase in demand for hospitals, which risk being overloaded in the absence of available capacity. Therefore, since the good functioning of the hospital care structure is fundamental for the delivery of care during a pandemic, many studies count the number of beds, distinguished by acute and intensive care, and the number of medical staff, including physicians, nurses and midwives, to assess hospital capacity level [33, 59]. In addition to the number of beds and staff, some papers also

Table 6 Key findings from Resilience in specific clinical areas group

Authors	Key findings
Altersberger et al. [67]	- A mild, though not significant, reduction in the number of patients treated with acute reperfusion therapy during lockdown was detected - Performance measures (onset-to-admission, admission-to-treatment time, admission-to-image, image-to-treatment time, admission to acute reperfusion therapies- EVT or intravenous thrombolysis- time) did not significantly differ before and after lockdown restrictions
Bronskill et al. [68]	- During the first wave there was an immediate and huge reduction in health service use for people suffering from dementia, Parkinson disease and neurodegenerative disease, concerning nursing home admissions (showing the largest decline), emergency department visits, physician visits, hospital discharges, home care visits - By the end of September 2020, most services had bounced back to historical levels, except for nursing home admissions - Weekly mortality rates increased for all patients considered between March and September 2020, with the largest relative increase among people with Parkinson disease and dementia with respect to people with neurodegenerative diseases - In-persons visits were gradually reintroduced but partially replaced by virtual visits
Caldarola et al. [35]	- Covid-19 pandemic had a destructive impact on cardiovascular mortality rate in Italy, due to a reduction in hospitalizations for acute coronary syndromes, an increase in the number of out-of-hospital cardiac infarction, a reduction of the number of cardiac check-ups, of the therapeutic and diagnostic services
Caldas et al. [50]	- A 22.3% reduction in the number of collaboration requests to Liaison Psychiatry patients was found in 2020 - The hospitalization length was lower in 2020 with respect to 2019 - The number of patients reporting suicidal ideation increased by 5.9% in 2020 with respect to 2019
Carroll et al. [51]	- During lockdown restrictions a significant reduction in weekly screenings and a decrease in number of diagnoses, specifically for regularly screened cancers (breast, cervical, colorectal, and prostate) was documented in North Carolina - After relaxing restrictions, weekly cancer screenings significantly increased
Cash et al. [24]	- An increase in the rate of out-of-hospital deliveries from mid-March through July 2020 was observed, before rebounding to similar pre-Covid rates - After lockdown measures, there was an increase of 6.3 out-of-hospital deliveries per week
Chandok et al. [52]	- Key care processes for diabetes I and II fell between 2019/20 and 2020/21 - Between 2019/20 and 2020/21 there was a decrease in the rate of emergency admissions for cerebrovascular accident and myocardial infarction - Admissions and rates for diabetic ketoacidosis and amputations were similar across the two study periods (i.e., before and after the pandemic), while admissions for diabetes mellitus and hypoglycaemia increased after Covid-19 - The largest decrease in emergency avoided admissions was observed for cerebrovascular accident and myocardial infarction
Douiri et al. [44]	- Under lockdown restrictions, there was a 12.4% decrease in stroke admissions. This decrease was statistically significant for ischemic stroke but not for primary intracerebral hemorrhage or undetermined stroke - The 7-day case fatality rate for stroke showed a significant 2.5% increase - Care quality had remained unchanged or even improved for all care quality indicators
El Moussaoui et al. [53]	- Since the beginning of the pandemic, a reduction in new HIV diagnoses has been observed - A similar decrease concerned the number of follow-up of people living with HIV (reflected by the number of consultations undertaken by sexual health services, psychologists and specialists in infectious diseases) as well as in several coinfections and comorbidities screening (hepatitis C, syphilis, rectoscopy/colonoscopy for colorectal, anal cancer screening, hypercholesterolemia, chlamydia and gonorrhea)
Glasbey et al. [43]	- Lockdown measures reduced the probability for a patient of receiving his planned cancer surgery. This result persisted even after correcting for local SARS-CoV-2 rates - Under full lockdowns, delays from diagnosis to operation were documented for operated patients, regardless of whether they were receiving neoadjuvant therapy
Greene et al. [54]	- There was a 15.2% decrease in diagnoses for female breast, colorectal and non-small cell lung cancers - A 41.6% reduction in stage I female breast cancer was observed in 2020 with respect to 2019, followed by a 20.5% reduction in stages II and a 18.2% reduction in stages III - There was an 86.7% reduction in screen-detected female breast cancer diagnoses in 2020 compared to 2019, mostly concentrated in the second quarter of the year - Despite remaining the most common pathway to diagnosis, a 19.9% reduction in GP urgent suspected cancer referral colorectal cancer diagnoses was signaled in 2020 compared to 2019

Table 6 (continued)

Authors	Key findings
Guddeti et al. [36]	- During the Covid-19 epidemic, a deep drop in STEMI (Segment–Elevation Myocardial Infarction) activations was documented across healthcare systems, specifically of about 29%, in USA, 23% in UK (from Jan to May), 26.5% in Italy (in March) - Substantial reductions in primary PCI (Primary percutaneous coronary intervention) rates for STEMI and in hospital admissions for STEMI and NSTEMI were found, despite more pronounced for the latter group - Given the shortage of appropriate resources due to the pandemic, fibrinolytic therapy was revaluated for the management of STEMI even in PPCI-capable hospitals
Hajdu et al. [55]	- Under Covid-19 restrictions, there was a 32% reduction in EVT (endovascular therapy) procedures - The analysis estimated also a 54-min increase in symptom onset-to-groin puncture time
Herranz-Larrañeta et al. [56]	- Although there was a reduction in the volume of Otolaryngology emergency department consultations between 2019 and 2020, differences are not significant when each month is individually compared - In 2020 the majority of consultations were due to: otalgia, odynophagia, and epistaxis - The number of adequate visits increased in 2020 with respect to 2019
Jankovic et al. [69]	- The number of spinal operations did not drop during the pandemic, compared to 2019 due to a 10.2% increase in emergency surgeries - There was a 14.2% increase in emergency transfers from smaller hospitals - There were a 0.5% not significant reduction in postoperative infections and a slight reduction in urinary tract infection and pneumonia in 2020 compared to 2019
Lesaine et al. [45]	- The stroke median EU admission-to-imaging time increased and the STEMI median first medical contact (FMC)-to-procedure time decreased from February to May 2020, compared to the pre-Covid period - The management time was permanently high for stroke and increased for STEMI in the period May–August 2020 - For patients having a recent ischaemic or haemorrhagic stroke diagnosed by brain imaging, the share of intravenous thrombolysis decreased between February and May 2020, as compared to the pre-wave and post-wave periods - The number of patients with an optimal pathway (calls to emergency services/mobile intensive care units transport/EU) was higher between February and May 2020, compared with the pre- and post-pandemic periods
Niu et al. [57]	- The number of HIV tests and ED-based HIV visits per month sharply decreased during Covid-19, compared to the pre-pandemic period. The reduction was more pronounced during the first wave of Covid-19 - The number of HIV tests per month bounced back to the pre-pandemic levels between October 2020 and March 2021
Quiros-Roldan et al. [25]	- The average monthly number of new HIV diagnoses moved from 6.4 between October and November 2019 to 2.5 between October and November 2020 - The number of out-patient visits at the HIV clinic was higher in 2019 than in 2020, also because of the increasing use of telemedicine during Covid-19 - Missing visits were significantly lower in 2019 than in 2020 - The number of patients receiving antiretroviral therapy decreased by 23.1% in 2020, compared to 2019
Robert et al. [37]	- There was a 11.4% decrease in urology hospitalizations in 2020, mostly concerning non-oncology field - The reduction in surgeries mainly concerned suburethral slings for female urinary incontinence (− 45%) and those related to prostate hyperplasia (− 21%), though kidney cancer (− 9%) and bladder cancer (− 6%) care were also affected - The public health system suffered the most from Covid-19 compared to the private system
Rydell et al. [46]	- There was a not significant reduction in the number of stroke and TIA (Transient ischemic attack) admitted patients in 2020, compared to 2019 - A significant increased delay from onset to arrival at the ED was observed in 2020, - The door-to-needle time to IVT was significantly lower in 2019 compared to 2020 - A significant reduction in the number of follow-ups at hospital outpatient stroke clinic of stroke and TIA patients was registered in 2020, compared to 2019
Singh and Edwards [26]	- 37% of respondents reported problems in getting health care and medication for gout in outpatient clinics, as well as in emergency rooms (17%) or in hospitals (17%). between April and June 2020
Soares et al. [49]	- Opioid overdose visits ED had a 10.6% increase in 2020 compared to 2018 and 2019, though a 14% reduction in all-cause ED visits - A 28.5% increase in overdose visit rates per 100 all-cause ED visits was registered

Table 6 (continued)

Authors	Key findings
Toro et al. [34]	- The annual patient volume for ophthalmology had an 81% drop between March and April 2020 - There was a 97% reduction in cataract surgery volume, and an overall reduction from 35% up to 93% in the number of monthly intravitreal injections administered for macular disorders between March and April 2020 - It can be estimated that each month of lockdown determined a reduction of about 50,000 cataract operations - Following Covid-19, many departments had put off from 57 to 100% of glaucoma treatments - There was also a deep decline in the access to emergency care for diseases such as ocular trauma, as well as cornea donations
Vignatelli et al. [58]	- All the indicators of healthcare services (i.e., outpatient visit, outpatient neurologic visit, outpatient physiotherapy evaluation or treatment, outpatient testing, non-urgent hospital admission) concerning patients suffering from Parkinson's disease (PD), atypical parkinsonism (AP), and vascular parkinsonism drastically dropped in the first wave of Covid-19 - Reductions persisted until September 2020 and mostly interested physiotherapy in people with PD - Outpatient healthcare service indicators were gradually restored after the first two week of pandemic, except for non-urgent hospital admissions - PD-related major clinical outcomes significantly increased between March and September 2020 compared to the corresponding period in 2019 - An association was found between PD-related major clinical outcomes and the reduction in the number of physiotherapy treatments in 2020
Weng et al. [38]	- In areas characterized by a low epidemic pressure, ophthalmologists should pursue volumes close to normal operating levels and guarantee adherence to safety protocols - In areas characterized by a high epidemic pressure, the optimal strategy should be based on the postponement of appointments and treatments for patients not suffering from Age-Related Macular Degeneration, except for monocular patients or patients with higher risks of irreversible visual impairment - In areas characterized by a severe epidemic pressure, only treatments to patients with nAMD (NEOVASCULAR age-related macular degeneration), with NVG (neovascular glaucoma), onset with significant vision loss, or to monocular patients should be guaranteed (all other treatments should be postponed)

consider hospital equipment such as the number of ventilators [39] and the number of personal protective equipment [63]. Other indicators commonly used are: day of hospitalization distinguished by department [27], occupation rates [28], Covid-19 infection rates [65], ED admissions distinguished by triage code [59] and number of critically ill/injured patients treated simultaneously that would overwhelm the ED resources [62]. As mentioned in the previous section, mortality rate distinguished by cause of death is also widely employed to assess the ability of a healthcare system to lessen the impact of a crowding event [33]. Lastly, Nunes and Ferreira [47] rely on specific process or quality care indicators such as the number of patients seen in the hospital by complexity and severity, the number of hip surgeries in the first 48 h after a fracture, the number of avoidable post-operative pulmonary embolisms and so on.

Shifting the attention to papers falling into Resilience indices group, proper resilience indicators are built, which focus attention on the hospital capacity to be prepared for the next health challenges also by virtue of the lessons learned during the last shock. For example, Coccia [30] generates two composite indexes: the resilience index, based on Covid-19 related indicators such as average mortality rate, hospital occupancy and Intensive Care Units occupancy per 100,000 people; the preparedness index that still builds on Covid-19 data such as the doses of vaccines administered, and the total vaccinates per 100,000 people. Similarly, Glasbey et al. [31] construct the surgical preparedness indicator, computed as the ratio of the actual number of surgical interventions to the expected surgical interventions according to pre-shock historical levels. Kuzior et al. [33] calculate an index of resistance to the pandemic through the relative difference between the number of infected people and the number of people dying because of Covid-19. Differently from Coccia [30], Riccardo et al. [40] develop a resilience indicator based on the number of staff members devoted to Covid-19 related issues (e.g., dedicated to contact tracing, to the collection of clinical samples etc.) and the number of infected people. Finally, Trucco et al. [42] introduce a set of performance measures among which the Weighted Waiting Time Index that is calculated as the weighted average of the waiting time of the last patient in queue in ED for each patient class (determined by the patients' critical conditions and triage code). Moving to Resilience forecasting models group, apart from the already mentioned metrics [32, 41, 42], in an attempt to evaluate the hospital's ability to be prepared to future outbreaks by predicting and anticipating critical healthcare issues, many scholars resort to performance indicators such as waiting times of patients to be admitted or hospitalized [29, 48, 61].

Table 7 Key findings from studies in Resilience and input capacities, Resilience indices and Resilience forecasting models groups

Authors	Key findings	Group
Berger et al. [27]	- The pre-pandemic availability of acute care beds was not overwhelmed by COVID-19 hospitalisations in any of the 11 countries analysed - The pre-pandemic intensive care capacity was exceeded by COVID-19-required admissions in the Netherlands, Sweden, and the Lombardy region - Intensive care capacity was almost surpassed in Belgium and Italy	Resilience in specific clinical areas
Cacace et al. [28]	- The German case demonstrates that being endowed with many spare beds might be crucial in responding to the crisis - High bed capacities, however, must be accompanied by the availability of (highly) qualified nursing staff - In the absence of available capacity, having an effective preparedness plan to adjust disposable capacity is essential from a crisis response perspective. Any strategy must be supported by available data on existing and built-up capacity, especially in intensive care, and a robust digital infrastructure - A centralised governance structure guarantees flexibility and adaptability in the use of pre-existing resources, in view of a rapid expansion of capacities. Coordinated actions and the existence of referral and treatment protocols certainly drive to better performances	Resilience in specific clinical areas
Coccia [30]	- On average, best performer countries in terms of resilience and preparedness had a population lower than 14 million of people, average health expenditure (in percentage of GDP) of about 8.6% and higher levels of the indexes of public governance - No country showed top-ranked performances in both indexes (with high resilience and high prevention capability) - Some countries demonstrated higher level of resilience but very few countries were highly prepared to prevent future epidemic outbreaks	Resilience indices
D'Aeth et al. [29]	- Using optimized schedules allow to gain years of life compared to adopting standard policies (i.e. prioritization policies adopted during Covid-19) - Largest gains under optimized schedules refer to neoplasms, digestive system diseases, and injuries and poisoning - Large differences between standard policies and optimized schedules are also found for diseases of the circulatory system and respiratory diseases	Resilience forecasting models
Davis et al. [61]	- The model employed allows to predict the likelihood of an imminent disaster-level event - Using the model predictions, administrators can adopt optimal strategies to prevent the consequences of the extreme event or to mitigate their impact	Resilience forecasting models
Duarte et al. [48]	- The COVID-19 pandemic significantly changed many emergency department indicators, differing from any model predictions - The number patients in department and that of patients' attendances (i.e., patients waiting to be seen in the ED and patients with major injuries attending the ED) were significantly lower between March and May 2020, before coming back to pre-Covid levels between May and June - A similar decrease was observed for the number of patients that have been attended, not discharged, but waiting to be admitted to the hospital between March and May 2020	Resilience forecasting models
Glasbey et al. [31]	- 74.6% hospitals were not able to maintain their planned surgical volume ratio during the COVID-19 pandemic, mostly in high income countries - Of the indicators used to construct the surgical preparedness index, the ones where hospitals got the best relative performances were: electricity supply, oxygen supply, and perioperative drugs - The indicators where hospitals obtained the worst relative performances were: ring-fenced critical care beds, remote outpatient appointments, and formal operational plan - The largest differences in performance across hospitals were observed in device supply, remote outpatients, and drug supply	Resilience indices
Jain et al. [64]	- The simulated scenario suggests that it may take from 7 up to 16 months for the USA health-care system to revert to pre-pandemic volumes of elective orthopaedic surgery - The paper estimates a cumulative backlog of > 1 million surgical cases at 2 years after May 2020	Resilience forecasting models

Table 7 (continued)

Authors	Key findings	Group
Kuzior et al. [33]	- The system constructed following the Beveridge principle turned out to be the best, thanks to the highest efficiency rate of 90% and a pandemic resistance rate of 98% - Four of the countries falling in the Beveridge group got the maximum efficiency level (Ireland, Iceland, New Zealand and Great Britain) - The second group of countries in terms of quality was that adopting the system built according to the Bismarck principle, having an 88% efficiency index in the medical field and 97% resistance to the pandemic - Ukraine, India and Portugal resulted to be the weakest in coping with the pandemic, showing very low scores of economic efficiency	Hybrid
Lupu and Tiganasu [65]	- Countries showing higher relative level of efficiency (0.75–1) were: Austria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Luxembourg, Malta, Norway (the only country reporting 1), Portugal, Slovakia, Slovenia, Switzerland - Countries reporting average efficiency (0.5–0.75) were: Belgium, Bulgaria, France, Germany, Greece, Hungary, Netherlands, Poland, Spain, Sweden, UK - Countries exhibiting low efficiency (< 0.5) were: Italy and Romania - Focusing on the first wave, the efficiency of health systems was negatively correlated with comorbidities, population age, and population density	Resilience in specific clinical areas
Manley et al. [62]	- Rural hospitals have limited surge capacity, with 95% reporting the potential overwhelm of emergency departments by 10 or fewer critically ill or injured patients - Hospitals involved in the survey are engaged in terrorism training but only few have experienced actual terrorist events - Hospitals express confidence in handling influenza-related events but may lack preparedness for a considerable increase in demand. Enhancing the response to influenza, which has broader applications than training for terrorist events, is suggested as a more effective training strategy - Rural hospital should train for the commonalities of different disasters, improving their response to any disaster, rather than for specific threats of rare events	Resilience in specific clinical areas
McCabe et al. [39]	- Among five interventions implemented in England during the COVID-19 surge (cancellation of elective surgery, setting up field hospitals, deploying medical and nursing students, using private hospitals, and bringing back former healthcare staff), cancellation of elective surgery made the largest contribution to increasing available capacity during the surge - Constraints in critical care were primarily related to the number of critical care nurses, emphasizing the need to sustain interventions like deploying former healthcare staff and using private healthcare provision - Recommendations include increasing the desirability of nursing, recruiting and training more critical care nurses, upskilling general and acute staff	Resilience in specific clinical areas
Muselli et al. [59]	- There was a 66.6% reduction in the overall emergency department visits during the COVID- 19 pandemic compared to 2019 - There was a significant increase of the hospitalization rates from 15 to 26% comparing the quarter March–May 2020 and the same period in 2019 - Focusing on the ward of hospitalization, there was an increase in admissions to surgical wards and ICU but a decrease in admissions to medical wards during the pandemic	Resilience in specific clinical areas
Nunes and Ferreira [47]	- The Covid-19 pandemic led to a decline in efficiency which rebounded back to its pre-pandemic levels in 2021 and 2022 entering the COVID-19 pandemic in 2020 seems to have led to an abatement of efficiency - Effectiveness instead significantly increased with the outbreak of the pandemic	Resilience in specific clinical areas
Riccardo et al. [40]	- The infectious diseases surveillance system in Italy allowed to well predict the occurrence of laboratory-confirmed severe and lethal infections within 3 weeks in the absence of additional control or mitigation measures	Resilience indices
Romani et al. [32]	- Between February and March 2020, the number of available ICU beds care shifted from 44 to 105, and from 449 to 962 beds, respectively in Modena and the whole Emilia-Romagna region	Resilience forecasting models

Table 7 (continued)

Authors	Key findings	Group
Trentini et al. [60]	- The number of hospitalized patients in ICU had been decreasing throughout the pandemic from 13.2% between February and March to 3.1% from April to July 2020 - A declining trend in ICU mortality was registered, going from 51.9% between February and March to 27.6% from April to July 2020 - The delay between hospital and ICU admission was larger between March and April 2020	Resilience in specific clinical areas
Trucco et al. [42]	- During the daytime scenario, for what waiting time performance is concerned, the proposed alternative resource allocation strategies provide better performances than the current PEMAF (Piano di Emergenza per il Massiccio Afflusso di Feriti, according to the current Italian nomenclature), under which ordinary activities are gradually or suddenly interrupted - During the night/holiday scenario, the proposed simulation allows detecting the most critical resources and improving the operational capacity of the ED to adequately treat red code patients	Hybrid
Wang et al. [41]	- The simulation model suggests that if the infectious disease is on the course of becoming endemic, it is needed to increase the medical resources, such the number of hospital beds, possibly implementing maximum treatment ratio to keep the infection under control	Resilience forecasting models
Winkelmann et al. [63]	- All countries adapted hospital departments to create COVID-19 designated units and expanded hospital and ICU capacity. Having sufficient resources is crucial in the early stages of the crisis to better cope with the growth of cases. Countries with a pre-existing high density of hospital and ICU beds had an advantage in meeting increased demand during the pandemic - Some countries created surge capacity by postponing non-urgent interventions, but only a part of this increased capacity was actually used, raising concerns on whether this might have jeopardized care for other conditions in vain - Adaptive surge capacity is crucial for resilient health systems, but adaptations must be informed by a real-time monitoring system and high-quality data, in relation to the evolving demand and available resources	Resilience in specific clinical areas

Finally, looking at the results, a relevant portion of literature, mostly falling into Resilience and input capacities group, shows that many health systems suffered from resources shortages during the pandemic or similar events, especially when looking at intensive care beds [27, 32], which must be accompanied by highly qualified and trained staff [28]. The problem was even exacerbated in rural hospitals, which typically have limited surge capacity and struggle with high staff turnover and staff shortages [62]. Among the various interventions that can be implemented to meet a sudden increase in demand (i.e., cancellation of elective surgery, reorientation of hospital departments, setting up of field hospitals, use of private hospitals, inter-hospital transport of patients, repurpose and redeployment of existing staff, deployment of medical and nursing students and return to work of former healthcare staff), cancellation of elective surgery was found to make the largest contribution to increasing available capacity during the Covid-19 surge in England [39]. Although the measures taken by different countries are influenced by the impact of the pandemic, as well as the initial infrastructure and organization of health systems (e.g. large private hospital sector, availability of beds, average bed occupancy rates), the implementation of comprehensive and well-coordinated measures is found to be crucial for supporting an optimal surge capacity response [63].

Regarding the other papers, some measure the countries' performances in terms of resilience and/or preparedness [30, 33, 47, 65] and find that the spread of a pandemic is generally responsible for large differences in efficiency levels among health systems. Besides critical care beds availability, further factors which are considered to be essential for resilience are the existence of an operational plan to face an emergency [31] and of a robust digital infrastructure [28]. Moreover, countries' rankings in terms of resilience depend on the population structure (i.e., age, density, comorbidity) [65] and on average health expenditure [30]. Finally, the Resilience forecasting models studies, which simulate alternative schedules or resource allocation strategies seem to improve results in terms of years of life saved [29] or of the general operational capacity of an emergency department [42], when compared to the standard procedures adopted. Additionally, the proposed models allow to predict the occurrence of an epidemic in good time to adapt medical resources to requirements [40, 41, 61].

Concluding remarks

Conclusions

The aim of this systematic literature review was to shed new light on metrics and indicators used in high-income countries to assess the resilience of hospital care systems when acute and large-scale health shocks occur.

We found a wide range of methodological approaches and strategies to measure hospital resilience, which differ not only in metrics but also in scope. Despite their peculiarities, however, all works in our final sample share the idea that metrics should never be considered useful in themselves but always because they suggest strategies and lines of action for policy makers. Most of the studies were conducted during or immediately after the onset of the described health shock (especially the Covid-19 pandemic). The search for a prompt operational response in the face of the shock mostly justifies the prevailing fragmented approach to the complex and multi-faceted problem of resilience, not leaving enough time to "metabolize" the experience. Indeed, when a health shock arises, the priority is to ensure that hospitals continue to carry out their healthcare functions, providing critical, life-saving and essential, quality and continuous services, without leaving anyone behind. Therefore, the need to quickly understand how to proactively manage this change and whether the hospital system was reacting positively required the development of quantitative measures based on readily available and accurate statistical data, either at the hospital, national or international level. The availability and accuracy of data has, therefore, placed a strong constraint on the development of metrics and indicators which, as a result, focus, from time to time, on specific aspects of hospital activity—those most easily detectable or considered most relevant.

However, hospitals are complex systems. In this sense, their ability to be resilient does not depend so much or only on the achievement of success in terms of one or a few capacities and functions, but rather on the adoption of a global approach to the problem and on the holistic awareness that only by activating a multiplicity of capacities, acting on multiple functions and relying on different resources, it is possible to overcome the disruptive event and the related demand surge.

Along with data availability, nuances and differences in conceptualization of hospital resilience are ultimately reflected in the diversity of assessment and measurement strategies, making the development of pragmatic, comprehensive, and validated measures even more difficult. Indeed, the majority of the 45 reviewed studies (i.e., the papers in Resilience specific clinical areas group) mainly look at the hospital system's capacity to respond quickly and decisively to the onset of the health shock, relying on their existing resources, namely the adaptive capacity. That is, studies in this group generally adopt a *resilience outcome* approach, also referred to as *revealed resilience* [72], as they focus on a post-shock evaluation of resilience outcomes rather than assessing resilience capacity in terms of preparedness before a shock occurs. The objective is not to determine whether a system was inherently resilient before an event but rather to measure how resilient it proved to be in practice. By focusing on service disruptions and performance changes, they frame resilience as the system's ability to maintain access to healthcare services and preserve critical functions during a crisis [73].

Such studies typically evaluated hospital resilience with reference to specific clinical areas, those experiencing greater pressure on their resources or where the possible consequences of disruption of patients' activity were likely to be more serious. Therefore, the indicators used are very sectoral, based on available routine clinical activity data, and focused on their greater or lesser deviation from the same measures in the pre-shock period. This comparison between two one-off measures can, however, lead to misleading conclusions, to the extent that it lacks a dynamic perspective of continuous monitoring of the hospital's resilience capacity over time and is not able to correlate the latter to the severity of the shock experienced.

Finally, a key limitation of using service disruptions as indicators of resilience is that they may result from a strategic reallocation of resources rather than a failure of the system itself. However, it is inherently difficult to determine whether such reallocation resulted in an unnecessary restriction of access to essential care. Regardless of intent, these disruptions may lead to unmet healthcare needs, delayed diagnoses, and the accumulation of deferred medical procedures [74]. This underscores the importance of complementing performance metrics with patient outcome data to better assess whether observed disruptions reflect an effective adaptive response or indicate an inability to maintain usual service standard.

The largest number of metrics, however, belong to the works included in what we have classified as Resilience and input capacities, and Resilience indices groups. In both cases the concept of resilience extends beyond simple adaptive capacity, although it remains still partial.

Specifically, in Resilience and input capacities works the adaptive capacity is evaluated alongside the absorptive capacity. This means shifting attention from the analysis of hospitals' pure reactions to disruptive events to that of their reflective and proactive strategies, which require reconfiguring the system without however envisaging radical and long-standing reforms (as in the case of transformative capacity). Therefore, resilience indicators no longer focus attention on hospitals' clinical outputs/outcomes but rather on the resources available to hospitals to increase their surge capacity preparedness, especially in three domains—namely beds, staff and equipment -, and regarding ICUs. Notwithstanding, they often overlook the fact that the needed resources must be available not only in the right quantities, but also in the right combination (mix), at the right time and place. The works in Resilience indices group are the most quantitative. Compared to the two previous groups, they rely on a hybrid approach to measure the resilience of hospital care systems, based on the evaluation of both clinical activity data and available resources. The intent here is to assess the hospital capacity to react to future health disruptive events but looking at the past and the lessons learned. They, therefore, broaden the addressed domains of resilience (i.e. absorptive and adaptive capacities), to include that of learning capacity. Noticeably, this approach requires a certain temporal detachment from the onset of the shock on which the experience is based. Accordingly, it is no coincidence that all the works in this group were published in 2022, the year in which the most critical waves of the pandemic had already passed. One of the limits of this approach (and even more so of the previous ones) is that it almost completely ignores the transformative capacity, which is fundamental during the management phase of the shock and a crucial dimension of the concept of resilience [73;74]. Focusing on how hospital care systems can reshape themselves and move towards long-lasting and more functional forms of care for society, transformative capacity also requires the adoption of innovations and novelties in the organizational and clinical practice of hospitals. Therefore, it implies a change of mentality in existing hospital resilience paradigms, which are undermined with the aim of imposing new ones, capable of guiding the transition towards a more resilient future. Among the various domains of resilience, therefore, the measurement of transformative capacity is the one that poses the greatest methodological difficulties and challenges, and this partly explains the lack of attention paid by the literature to this aspect. Finally, the Resilience forecasting models group uses predictive and simulation models to anticipate and optimally plan hospital response to future health shocks. Although promising, very few works in our final sample consider such an approach as it requires continuous monitoring and iteration to incorporate new data, feedback, and change into the models. Once again, this feedback loop process takes time and cannot occur in the immediacy of the pandemic.

Limitations and further extensions

This systematic review has some limitations, mainly due to the inclusion and exclusion criteria, which were strictly defined by its scope as well as to the reviewed literature itself. Funded by two international projects (see Acknowledgments), the review aimed to collect all existing quantitative measures of resilience to later (as a further step of the projects) develop a comprehensive unified indicator. As a result, it focused exclusively on quantitative studies, leading to the exclusion of qualitative research and grey literature. Although relevant sources from grey literature (e.g., conference papers or government reports) were then identified through snowballing, they were ultimately excluded due to the absence of pre-existing or proposed quantitative indicators.

Given the inclusion restrictions, this review highlights the well-documented challenge of the current literature in measuring transformative resilience [see also 74],[14] which often relies on intangible factors. Studying transformation requires qualitative data, such as changes in organizational structures or strategic planning [75], which take time to become available but also difficult to translate into objective quantitative measures. Moreover, even when available, data related to transformation is often complex and unstructured, necessitating advanced tools like Artificial Intelligence (AI) [76] to be analyzed effectively [76]. AI facilitates the use of Big Data, enabling the analysis of extensive datasets containing information on thousands of patients.[15] This approach allows researchers to develop more sophisticated predictive models [77], offering valuable insights into how health systems can achieve lasting and effective transformations. In the end, while we acknowledge that qualitative studies could offer valuable insights into leadership, coordination, and organization, their omission was necessary to maintain a systematic, measurable approach to resilience assessment.

[14] We draw on the definition by [82], which describes transformative capacity as 'the ability to transform functions and structures, involving significant organizational changes.'.

[15] According to [83], linking clinical registries, which focus on short-term scenarios with administrative datasets can be highly beneficial. This integration creates longitudinal registries that track follow-up information, enabling a more comprehensive assessment of long-term hospital performance. In turn, this allows for a better evaluation of resilience over time, particularly in terms of transformative capacity.

Closely related to this, the review does not address long-term resilience due to the timing of its conduction (immediately after the shock) and the fact that this aspect of resilience would also require considering intangible factors. Most studies were conducted during or shortly after the health crisis, often overlooking long-term adaptation, lessons learned, and future preparedness. In this view, replicating the research with a time lapse to include longitudinal studies tracking resilience over time would provide valuable insights into how hospitals adapt and evolve beyond the immediate response phase.

Additionally, as noted by [78], "*community health institutions, households, and broader community networks play critical roles in health system recovery and response during shocks.*" National and international institutions provide financial and logistical support, while also strengthening leadership and coordination through updated guidelines and strategies. Drawing from the concept of Resilient Health Care (RHC) [79, 80], resilience should be seen as a collective phenomenon that emerges from the interconnection between health professionals, organizations, and patients. Future research should adopt a more comprehensive approach, considering not only organizational improvements but also the relationship between resilience and quality of care. However, this requires measuring organizational and intangible factors and providing outcome measures, which are not always available.

Finally, while some studies addressed broader events such as mass-casualty incidents or general crowding events [31, 41, 42, 61, 62], allowing for the generalizability of the findings to any health shock, the dominance of Covid-19 studies means that resilience metrics and strategies tailored to this specific shock may not fully apply to different contexts, such as natural disasters or localized outbreaks, especially when they refer to low-middle income countries. In fact, a major challenge in low-middle income countries is the lack of a robust data collection infrastructure. Important information, like records of routine clinical activities, is often missing, making it hard to use the original metrics. These metrics may need to be simplified to rely on fewer datasets. In addition, hospitals in low-middle income countries often face shortages of financial resources, staff, and equipment, which weakens their capacity to respond and adapt to shocks.

Overall, our conclusions are quite consistent with those of other (systematic and non-systematic) reviews [17, 81] that consider metrics and indicators used to assess the resilience of healthcare systems in general, and not of hospitals in particular. With them, we share the hope that future research will be addressed toward operationalizing a more comprehensive and systematic perspective of hospital resilience, incorporated into composite indicators capable of considering the different domains of the concept, the existing trade-offs between their respective strategies but also the country-specific, dynamic and feedback loop nature of the resilience process. In a nutshell, no single indicator can comprehensively capture resilience. Each indicator should be designed to interact with others, providing a comprehensive overview of resilience across different dimensions and phases of a health shock. For example, absorptive capacity indicators (e.g., waiting times, bed occupancy rates) must connect with adaptive metrics (e.g., surge capacity) to ensure that maintaining baseline operations does not prevent the system from adjusting dynamically to evolving needs. In their turn, transformative capacity metrics (e.g., adoption of new technologies) must be informed by data from absorptive and adaptive phases, creating a feedback loop that strengthens the system over time. This framework ensures that the indicators accurately capture the system's ability to withstand, adapt to, and learn from health shocks, thereby supporting policymakers in making strategic decisions to build more resilient healthcare systems.

Appendix 1

Table 8 Studies in the sample

Authors	Journal	Method	Health Shock	Group
Altersberger et al. [67]	Stroke	Prospective multicenter cohort analysis	Covid-19	Resilience in specific clinical areas
Berger et al. [27]	Health policy	Cross-country analysis	Covid-19	Resilience and input capacities
Bronskill et al. [68]	JAMA Health Forum	Population-based repeated cross-sectional analysis	Covid-19	Resilience in specific clinical areas
Cacace et al. [28]	Health Economics Policy and Law	Cross-national comparative case analysis	Covid-19	Resilience and input capacities
Caldarola et al. [35]	Giornale Italiano di Cardiologia	Descriptive	Covid-19	Resilience in specific clinical areas
Caldas et al. [50]	International Journal of Psychiatry in Clinical Practice	Retrospective and descriptive analysis	Covid-19	Resilience in specific clinical areas
Carroll et al. [51]	Preventive Medicine	Time series regression	Covid-19	Resilience in specific clinical areas
Cash et al. [24]	Prehospital Emergency Care	Cross-sectional analysis	Covid-19	Resilience in specific clinical areas
Chandok et al. [52]	Practical Diabetes	Audit analysis	Covid-19	Resilience in specific clinical areas
Coccia [30]	Environmental Research	Index development	Covid-19	Resilience indices
D'Aeth et al. [29]	Nature Computational Science	Linear programming framework	Covid-19	Resilience forecasting models
Davis et al. [61]	Journal of Operations Management	Predictive model	Crowding event	Resilience forecasting models
Douiri et al. [44]	Stroke	Prospective registry-based cohort analysis	Covid-19	Resilience in specific clinical areas
Duarte et al. [48]	Applied Sciences	Time series, forecasting model, machine learning	Covid-19	Resilience forecasting models
El Moussaoui et al. [53]	HIV Research & Clinical Practice	Retrospective observational analysis	Covid-19	Resilience in specific clinical areas
Glasbey et al. [43]	The Lancet Oncology	International, prospective, cohort analysis	Covid-19	Resilience in specific clinical areas
Glasbey et al. [31]	The Lancet	Index development, country-level analysis, cross-sectional hospital assessment analysis	Airborne pandemic and non-airborne pandemic, seasonal pressures	Resilience indices
Greene et al. [54]	British Journal of Cancer	Retrospective observational analysis	Covid-19	Resilience in specific clinical areas
Guddeti et al. [36]	Cardiology clinics	Review	Covid-19	Resilience in specific clinical areas
Hajdu et al. [55]	Stroke	Retrospective observational analysis	Covid-19	Resilience in specific clinical areas
Herranz-Larrañeta et al. [56]	American Journal of Otolaryngology	Descriptive and analytical observational retrospective analysis	Covid-19	Resilience in specific clinical areas
Jain et al. [64]	The Journal of bone and joint surgery	Monte Carlo simulations	Covid-19	Resilience forecasting models
Jankovic et al. [69]	Frontiers in Surgery	Retrospective analysis	Covid-19	Resilience in specific clinical areas

Table 8 (continued)

Authors	Journal	Method	Health Shock	Group
Kuzior et al. [33]	International Journal of Environmental Research and Public Health	Scientometric analysis, index development, data envelopment analysis	Covid-19	Hybrid
Lesaine et al. [45]	BMJ open	Registry-based cohort analysis	Covid-19	Resilience in specific clinical areas
Lupu and Tiganasu [65]	Health Economic Review	Data envelopment analysis	Covid-19	Resilience and input capacities
Manley et al. [62]	Disaster Management & Response	Survey	Mass-casualty incident	Resilience and input capacities
McCabe et al. [39]	BMC Medicine	Model of deterministic linear equations	Covid-19	Resilience and input capacities
Muselli et al. [59]	Annali di Igiene, Medicina Preventiva e di Comunità	Retrospective analysis	Covid-19	Resilience and input capacities
Niu et al. [57]	American Journal of Infection Control	Before-and-after comparison and interrupted time series analysis	Covid-19	Resilience in specific clinical areas
Nunes and Ferreira [47]	Sustainability	Network data envelopment analysis model	Covid-19	Resilience and input capacities
Quiros-Roldan et al. [25]	AIDS research and therapy	Retrospective observational analysis	Covid-19	Resilience in specific clinical areas
Riccardo et al. [40]	Bulletin of the World Health Organization	Risk assessment tool	Covid-19	Resilience indices
Robert et al. [37]	BMJ open	Observational descriptive analysis	Covid-19	Resilience in specific clinical areas
Romani et al. [32]	Population Health Management	Deterministic compartmental model	Covid-19	Resilience forecasting models
Rydell et al. [46]	Journal of Stroke and Cerebrovascular Diseases	Cohort analysis	Covid-19	Resilience in specific clinical areas
Singh and Edwards [26]	Therapeutic Advances in Musculoskeletal Disease	Online cross-sectional survey	Covid-19	Resilience in specific clinical areas
Soares et al. [49]	Annals of Emergency Medicine	Multicenter, retrospective, cross- sectional analysis	Covid-19	Resilience in specific clinical areas
Toro et al. [34]	European Journal of Ophthalmology	Commentary	Covid-19	Resilience in specific clinical areas
Trentini et al. [60]	American Journal of Epidemiology	Retrospective observational analysis	Covid-19	Resilience and input capacities
Trucco et al. [42]	Disaster medicine and public health preparedness	Index development, discrete event simulation and system dynamics	Mass-casualty incident	Hybrid
Vignatelli et al. [58]	Frontiers in neurology	Retrospective cohort analysis	Covid-19	Resilience in specific clinical areas
Wang et al. [41]	Mathematical Biosciences & Engineering	Filippov epidemic model	Endemic such as severe acute respiratory syndrome, HIV and Ebola	Resilience forecasting models
Weng et al. [38]	Journal of the Chinese Medical Association	Review	Covid-19	Resilience in specific clinical areas
Winkelmann et al. [63]	Health Policy	Survey	Covid-19	Resilience and input capacities

Appendix 2

Search strategy.

- WEB OF SCIENCE

TS =((“hospital*” AND (“health system*” OR “healthcare system*” OR “health care system*” OR “health service*” OR “healthcare service*” OR “health care service*” OR “health organi*ation*” OR “healthcare organi*ation*” OR “health care organi*ation*”) NEAR/3 (“Stress test*” OR metric* OR indicator* OR assess* OR measur* OR quantif* OR scale OR framework* OR analys* OR evaluat* OR monitor* OR Resilience OR resilient OR resiliency OR attribute* OR surveillance)) AND (“hospital*” AND (“health system*” OR “healthcare system*” OR “health care system*” OR “health service*” OR “healthcare service*” OR “health care service*” OR “health organi*ation*” OR “healthcare organi*ation*” OR “health care organi*ation*” OR “health surveillance system*”) NEAR/7 (shock* OR vulnerable OR vulnerabilit* OR fragile* OR fragiliti* OR pressure* OR insecurity OR insecurities OR crisis OR crises OR disaster* OR outbreak* OR threat* OR overwhelm* OR disrupt* OR disruption* OR disturb* OR unpredictable OR pandemic* OR epidemic* OR outbreak* OR instabilit* OR war* OR conflict* OR flu*)))

- OVID MEDLINE ALL

1) "Delivery of Health Care"/og, sn OR ("Delivery of Health Care"/AND Evaluation Studies as Topic/) AND ((health system* OR healthcare system* OR health care system* OR health service* OR healthcare service* OR health care service* OR health organi?ation* OR healthcare organi?ation* OR health care organi?ation*) adj4 (Stress test* OR metric* OR indicator* OR assess* OR measur* OR quantif* OR scale OR framework* OR analys* OR evaluat* OR monitor* OR Resilience OR resilient OR resiliency OR attribute* OR surveillance OR flu*) AND (hospital*)).ti,ab
2) "Delivery of Health Care"/og, sn OR ("Delivery of Health Care"/AND Evaluation Studies as Topic/) AND ((health system* OR healthcare system* OR health care system* OR health service* OR healthcare service* OR health care service* OR health organi?ation* OR healthcare organi?ation* OR health care organi?ation* OR health surveillance system?) adj8 (shock* OR vulnerable OR vulnerabilit* OR fragile* OR fragiliti* OR pressure? OR insecurity OR insecurities OR crisis OR crises OR disaster* OR outbreak* OR threat* OR overwhelm* OR disrupt* OR disruption* OR disturb* OR unpredictable OR pandemic* OR epidemic* OR outbreak* OR instabilit* OR war? OR conflict? OR flu*) AND (hospital*)).ti,ab

- SCOPUS

(TITLE-ABS-KEY ("resilien*"OR"strengthening") AND TITLE-ABS-KEY ("Stress test*"OR"metric*"OR"indicator*"OR"assess*"OR"measur*"OR"quantif*"OR"scale"OR"framework*"OR"analys*"OR"evaluat*"OR"monitor*"OR"attribute*"OR"surveillance") AND TITLE-ABS-KEY ("system*"OR"organisation") AND TITLE-ABS-KEY ("health"AND"hospital"AND"healthcare"OR"health-care"OR"health care") AND TITLE-ABS-KEY ("crisis"OR"disaster"OR"epidemic"OR"pandemic*"OR"flu")

Author contributions All the authors contributed to the study conception and design, performed title/abstract and full-text screening, contributed to the critical revision of the manuscript for intellectual content and approved the final draft submitted for publication.

Marina Cavalieri and Domenica Romeo contributed to data extraction and wrote the first draft of the manuscript. Stefania Fontana contributed to the snowballing. Marina Cavalieri contributed to the Bibliographic analysis and summarizing results. Domenica Romeo contributed to the data interpretation and summarizing results.

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