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The status of the scientific consensus on resilience: Convergence, divergence and diversification[☆]

Maria Nogal [a], Omar Kammouh [b,*], Hiba Baroud [c]

[a] Faculty of Civil Engineering and Geosciences, Technical University of Delft, Delft, 2628 CN, Netherlands
[b] Faculty of Technology, Policy and Management, Technical University of Delft, Delft, 2628 BX, Netherlands
[c] Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, TN 37235, USA

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ABSTRACT

This paper critically examines the state of scientific consensus in the multidisciplinary field of resilience, a topic that has attracted increasing attention across different domains due to increasing societal and environmental challenges. The diversity of definitions, perspectives, and approaches within the field has resulted in a complex landscape, challenging the achievement of a comprehensive consensus. The main question addressed in this work is whether the scientific community is converging towards or diverging from a resilience consensus. The study also seeks to understand the specific circumstances under which convergence or divergence may be considered beneficial or counterproductive. The findings of this analysis bear significant implications for the future of research and education within the domain of resilience. The authors' primary observation suggests that achieving a well-thought-out balance between convergence and divergence can facilitate progress towards a wider consensus on resilience, ultimately fostering robust interdisciplinary collaborations and enhancing the practical utility of the concept. Furthermore, we propose pragmatic steps for promoting a shared understanding and a common framework in resilience research and practice.

1. Introduction

In recent years, the concept of resilience has gained increasing attention across various disciplines and fields of study [1]. As societies and ecosystems face growing challenges and uncertainties, understanding and enhancing resilience is becoming an increasingly important goal. However, the multidisciplinary nature of resilience research has led to a diversity of definitions, perspectives, and approaches, raising questions about the potential of a scientific consensus in the field. Achieving a robust and well-informed understanding of resilience while fully exploiting its potential for use requires balancing the need for knowledge convergence and divergence.

Knowledge convergence (or consensus) refers to the process of bringing multiple sources of information, expertise, and perspectives together to reach a common understanding or agreement on a particular topic or issue [2]. This can involve integrating and reconciling information that can be either conflicting or inconsistent. On the other hand, knowledge divergence occurs when new perspectives or understandings conflict with existing knowledge, which can result in the fragmentation of understanding and the spread of misinformation or misunderstanding that can potentially hinder progress on research and implementation [3]. However, knowledge divergence could also lead to the development of new and innovative perspectives and ideas, as well as the expansion and refinement of existing knowledge.

Generally, the greater the potential of an idea or concept, the more popular it becomes [2]. With increasing popularity, new perspectives emerge that can either strengthen the concept through convergence or impede its progress through excessive divergence. To examine the concept of resilience's popularity over time, this study adopts the hype-cycle model [4]. This model provides insight into the relationship between human expectations for a new technology and the actual maturity of that technology. Campani and Vaglio [5] formalize the hype-cycle model to describe the growth of scientific research impact. Accordingly, the characteristic curve of the model can be interpreted as the result of combining two fundamental growth processes. The first, represented by a logistic function, captures the evolution of a new and attractive scientific domain; its influence initially grows exponentially, then gradually levels off, and eventually experiences a decline in its growth rate as the field approaches saturation. The second process, which begins after a certain delay, reflects the emergence and diffusion of technological applications derived from that scientific foundation.

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* Corresponding author.
E-mail address: o.kammouh@tudelft.nl (O. Kammouh).

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The underlying premise is that technological progress builds upon the cumulative body of scientific knowledge. As shown in Fig. 1, the popularity of resilience by its usage level is tracked over time, as indicated by the upper blue line. Key foundational developments are also included and labeled from keystone K1 to K11, to monitor the concept's maturity.

The initial part of the curve (solid blue line) is derived from observed data, while the latter part (dashed blue line) is based on a likely scenario predicted by the hype-cycle model. There is a broad consensus among researchers that the variable of visibility or expectations can be quantified through the volume of publications referencing a specific technology, encompassing both academic and non-academic sources such as news media [4]. Nevertheless, as noted by [6], mainstream publications may provide an incomplete picture of hyped dynamics, emphasizing the importance of complementing such data with scientific literature. Accordingly, two sources have been used, information provided by Google Ngram Viewer which tracks the frequency of the term 'resilience' in printed sources in Google's text collections from 1974 to 2019, and data from ScienceDirect database spanning 1974 to 2023, reflecting the frequency of this term in scientific publications. The two sources present a correlation of 97% (based on the Pearson Correlation Coefficient) indicating a strong alignment between public and scientific interest in the concept of resilience over time. Note that units are excluded, focusing instead on identifying trends. For the projected part of the curve (dashed blue line), following the hype-cycle model, we anticipate a spike in usage (*Peak of Inflated Usage*), followed by a decline due to unfulfilled expectations (*Trough of Disillusionment*). Eventually, as Resilience Science matures, we expect the curve to stabilize, reflecting a realistic appraisal of the concept (*Slope of Enlightenment*).

Fig. 1 and Table 1 also highlight key events that have significantly influenced the field of resilience, such as the 9/11 Attack in 2001, Hurricane Katrina in 2005, and the COVID-19 pandemic in 2019. These events resulted in the term 'resilience' being used 42%, 72%, and 68% more than the average usage in the three years preceding and following them, respectively. The emphasis shifted towards climate-change resilience, particularly after Hurricane Katrina, while economic and business resilience became more prominent following the global financial and digital crises.

In response to these disruptive events, the concept of resilience has been increasingly explored by researchers and institutions. Efforts to understand and enhance resilience for better preparation, response, and recovery from such events have led to significant initiatives, like the 100 Resilient Cities by the Rockefeller Foundation and the creation of the standardization document [7]. However, the popularity of the concept of resilience has also led to its overuse, often without directly contributing to the core concept, especially in the case of research examining related concepts such as risk, reliability, vulnerability and sustainability. This trend has introduced a degree of 'noise' in the literature. The actual application of resilience, as opposed to its superficial use, is represented by the red line in the figure.

The presence of noise in the literature, primarily due to ambiguous ideas and concepts, hinders the convergence in the field of resilience. Determining the precise extent of this noise requires further analysis that falls outside the scope of this study. However, the authors anticipate that the disillusionment stage will mostly affect the casual and overgeneralized use of resilience, rather than its focused and intentional application.

This paper investigates the current state of consensus in the field of resilience, with a focus on technical domains and their interactions with social systems. While our discussion draws insights from ecological, psychological, and biological domains, these are not the primary focus here. The goal of this study is to examine the risks and challenges in achieving consensus in resilience research and practice and offer recommendations for advancing towards a common framework and shared understanding of the concept. The key question addressed is whether the field is moving towards a unified understanding of resilience or diverging in its interpretations and applications. By exploring and addressing the factors influencing the scientific consensus process, this work aims to contribute to a more comprehensive and unified resilience concept, ultimately benefiting research and application across various domains.

The rest of the paper is organized as follows. Section 2 discusses the current state of convergence within the field of resilience and the factors that influence the pace of convergence. Section 3 examines whether the field is converging or diverging in understanding resilience, highlighting key trends and patterns. Section 4 identifies some of the barriers that are hindering the achievement of scientific consensus on resilience. Section 5 focuses on the risks and opportunities associated with convergence, related to both research and education. In Section 6, we present a call for pragmatic action, suggesting strategies to move the field forward towards a more unified understanding. The paper concludes in Section 7, summarizing the key findings and offering reflections on future directions for resilience research and practice.

2. Scientific consensus on the resilience concept

To determine whether the scientific community is converging or diverging in its understanding of the resilience concept, it is essential to first understand the process of scientific consensus. Examining the landscape of scientific literature on consensus helps to gain insights into the temporal structure of scientific consensus as outlined in various studies [2,3].

The process of scientific consensus is depicted in Fig. 2. Initially, as the topic gains interest, new scholars emerge, and their opinions align with those of established experts, leading to an increase in scientific consensus (i.e., premature consensus). However, as more experts enter the field and new ideas are introduced, competing opinions and debates arise, causing a decline in scientific consensus. This decline can be critical if the scientific community does not work to bring consensus back to an upward trajectory. At a certain point, referred to as the 'pivot point' the scientific consensus will either continue to decline (divergence) or increase again (convergence). This critical point is influenced by the efforts of the scientific community to reach a shared understanding of the topic, such as through conducting more research, facilitating open communication, and encouraging the use of standardized protocols. It is essential for the scientific community to actively work towards consensus to ensure a common understanding of the topic and effective progress in the field.

The conceptual model presented in Fig. 2 synthesizes established theories and empirical findings from multiple research sources on scientific consensus dynamics. The model's temporal structure builds primarily on the empirical work of Shwed and Bearman [3], who documented non-linear patterns in scientific consensus evolution, and Ford et al. [2], who examined consensus dynamics specifically in multidisciplinary fields. The concept of alternating phases of convergence and divergence draws from Kuhn's [13] seminal work on paradigm shifts and scientific revolutions. The formation of distinct schools of thought during consensus decline is supported by both theoretical models of opinion dynamics in scientific communities [14,15] and empirical studies of intellectual clustering in science [16]. Recent quantitative Science-of-Science research [17,18] provides large-scale empirical validation of knowledge convergence and divergence patterns through citation and collaboration network analyses.

During the fluctuations of consensus, particularly during the phase of decline, a notable phenomenon usually occurs — the creation of distinct schools of thought. These intellectual clusters emerge as scientists and scholars adopt differing opinions, methodologies, and interpretations, contributing to a localized convergence within each school of thought. While members of a particular school may experience a high degree of consensus, this unity is localized, reflecting a form of agreement that is not universally shared across the broader scientific

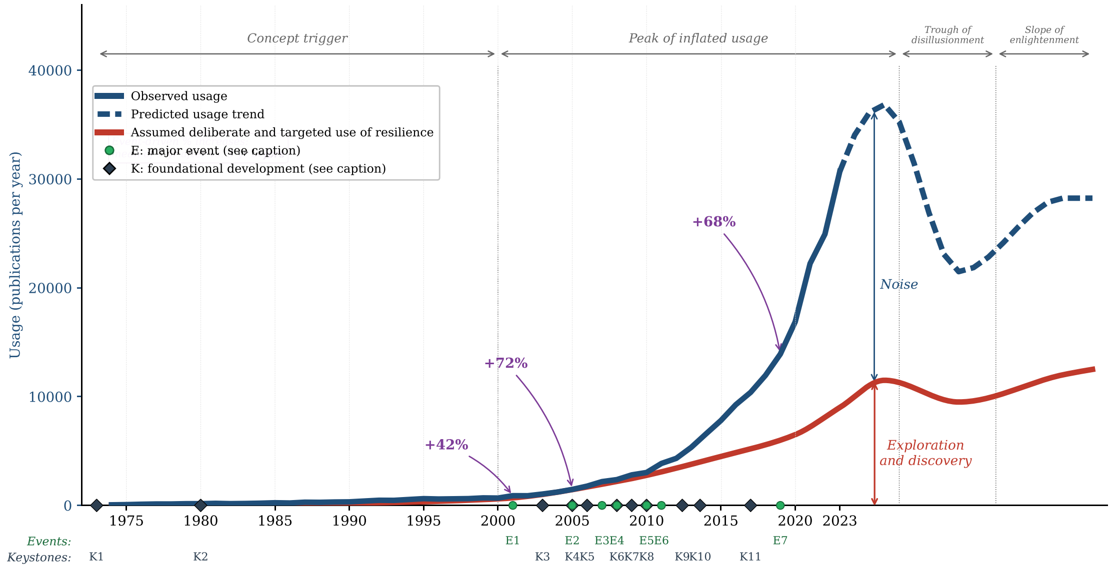

Fig. 1. Evolution of the usage level of the concept of resilience.

Table 1
Major events and foundational developments in the evolution of the resilience concept.

Major events		Foundational developments	
E1	9/11 Attack (2001)	K1	Ecological Resilience [8]
E2	Hurricane Katrina (2005)	K2	Psychological Resilience
E3	Global Financial Crisis (2007)	K3	Urban Resilience [9]
E4	Sichuan Earthquake in China (2008)	K4	Climate-change resilience
E5	Drought in the Horn of Africa, Stuxnet (2010)	K5	The National Infrastructure Protection Plan [10]
E6	Fukushima Daiichi nuclear disaster, Christchurch Earthquake in New Zealand (2011)	K6	Resilience in Economics and Business
E7	COVID-19 Pandemic (2019)	K7	Terminology on Disaster Risk Reduction [11]
		K8	Digital and Cyber Resilience
		K9	Climate Adaptation and Resilience Efforts [12]
		K10	100 Resilient Cities (www.100resilientcities.org)
		K11	ISO 22316:2017 - Security and resilience [7]

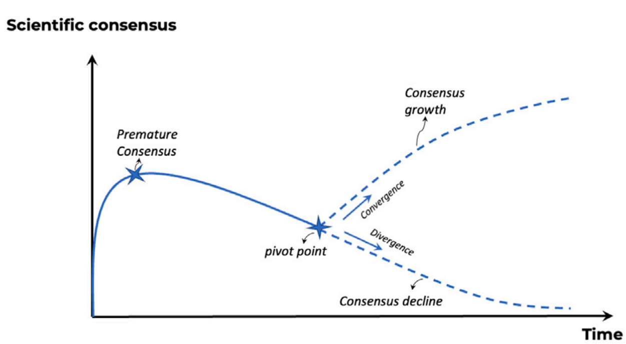

Fig. 2. Evolution of the scientific consensus as topic gains interest.

community. Thus, a paradoxical landscape of consensus is formed, marked by localized convergence within a global divergence.

Following the evolution of scientific consensus (Fig. 2), several crucial questions emerge that require contemplation. First, how can we determine our current position in this trajectory of scientific consensus? Second, how can we determine the inflection point and identify our current standing in relation to it? Third, are we at a juncture that is conducive to actively promoting convergence?

To explore these questions, this study outlines a four-stage progression from the conceptual understanding of resilience (ontology) to its practical application (operationalization), as depicted in Fig. 3.

- Ontology concerns the fundamental nature and structure of entities themselves, independently of any further considerations or even of their actual existence [19]. Accordingly, this stage involves identifying the core concept of resilience, focusing on its fundamental attributes and relationships. Based on the authors' experience and in alignment with other key references (e.g., [20–22]), the entity "resilience" can be categorized as a property of a system, entity, or individual denoting the ability to resist, absorb, accommodate, adapt to, transform and recover from various shocks and stresses.
- Ontological definition is the "description of entity classes, or relationships that represent their essential properties, in such a way that the defined entities are uniquely and fully specified" [23]. In this stage, the general concept of resilience is further contextualized. For example, when referring to the built environment, resilience might be defined as the capability of buildings, infrastructure, and communities to prepare for, absorb, adapt to, recover from, and learn from adverse events such as natural disasters or technological hazards. Here, the class "built environment" comprises the subclasses buildings, infrastructure, and communities. Similarly, the class "adverse events" includes the subclasses of natural disasters and technological hazards.
- Operational definition is described by [24] as "the specific formulation of a concept adopted by a particular researcher or group of researchers, usually expressed through an explicit definition". Adcock and Collier transition from a broad concept corresponding to the ontological definition to a systematized concept aligned with the operational definition. This definition translates the concept into practical terms, outlining how resilience can be observed, measured, and evaluated within the given domain. It

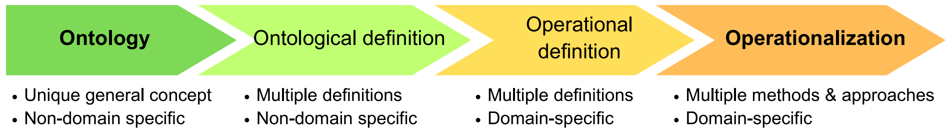

Fig. 3. Stages of ontological progression.

serves as a bridge between theoretical understanding and practical assessment. In alignment with the previous example, resilience of the built environment can be operationally defined as the ability of a road traffic network to maintain an acceptable level of serviceability during adverse events, from the onset of the hazard to the complete recovery of the network.

- Operationalization enables the transition from the systematized concept to observable indicators or measures suitable for empirical evaluation [24]. That is, the final stage involves the actual implementation of the operational definition. Here, the theoretical construct of resilience of the built environment, operationalized for road traffic networks is translated into concrete metrics (e.g., road saturation degree, travel time), assessment tools (e.g., resilience assessment tool based on dynamic thresholds [25]), or procedures (e.g., [26]). While economic loss or cost can be used as one indicator of resilience, many relevant dimensions (e.g., loss of trust of transport users and degradation of service quality) cannot be adequately translated into monetary units without significant loss of meaning. This highlights that economic indicators constitute only one component of a broader operational space required to quantify resilience. This stage is critical for empirically evaluating resilience, allowing researchers and practitioners to measure, compare, and enhance resilience capacities in real-world scenarios.

In examining the scientific consensus of resilience, a distinction should be made between divergence and diversification. Considering convergence at the ontological level, the scientific community believes that there is a general agreement on the fundamental characteristics of resilience. This indicates convergence on the concept. However, this consensus does not preclude the existence of diverse ontological definitions. It is important to recognize that these variations in definitions do not automatically imply a divergence from the core concept of resilience. These variations are acceptable as long as they maintain fidelity to the essential elements that define resilience.

Divergence occurs when there is a deviation from these core elements, either through the addition of extraneous characteristics or the omission of critical ones. This leads to the creation of definitions that depart from the commonly accepted understanding of resilience. The extent of this divergence is contingent upon the degree of acceptance these new definitions receive within the scientific community. For instance, a proposed definition that does not gain widespread acceptance is not necessarily indicative of a significant divergence within the field.

Conversely, diversification refers to the variety of definitions and methods for defining and implementing the concept of resilience. This diversity is not inherently a sign of divergence, provided that it remains true to the core ontological concept of resilience. Such diversification can be seen as a healthy exploration of the concept within different contexts and applications, contributing to the richness and adaptability of resilience as a field.

In the progression depicted in Fig. 3, varying levels of agreement or convergence can be observed across the four stages. It is crucial to understand that any divergence at one stage, particularly at the ontological or conceptual level, has the potential to affect the subsequent stages of discussion and application. Therefore, a thorough understanding of the differences between convergence, diversification, and divergence, and their respective impacts on the field, is important for our ongoing discussion in this paper.

3. Are we converging or diverging?

To understand the trajectory of resilience, we compare it with two closely related thematic areas, namely sustainability and risk. Fig. 4 and Table 2 report the relative frequency of the terms resilience, sustainability and risk in Google Books between 1970 and 2022, as retrieved from the Google Ngram Viewer. To capture the deliberate scientific use of the concept of risk, the search has been restricted to risk assessment and management; this restriction mirrors the distinction in Fig. 1 between the general usage of the term (upper, blue curve) and its deliberate, targeted use (lower, red curve). The three concepts exhibit clearly distinct trajectories. Sustainability followed a hype-cycle trajectory broadly comparable to that of resilience, with rapid growth from the late 1980s onward. However, sustainability reached a substantially stronger operational consensus through widely adopted frameworks such as ISO 14001 [30], the UN Millennium Development Goals (2000), and the Sustainable Development Goals [33], even while its ontological framings continued to diversify. Risk, in contrast, is a considerably older field with a more stable ontology and an earlier operationalization through standards [28,29,31]. This earlier consolidation is reflected in Fig. 4 by the marked plateau in the use of risk assessment and management after approximately 2007, consistent with what the hype-cycle model would describe as a slope of enlightenment, in which the concept reaches a stable level of usage following its operational maturation. Resilience, by comparison, is still in the ascending portion of its trajectory and has not yet reached an analogous plateau, suggesting that the field is in an earlier stage of operational consolidation than risk and has yet to develop the kind of widely accepted operational frameworks identified in the risk area. This comparison reinforces a central observation of the present work. While ontological agreement around the core concept of resilience appears relatively broad, the operational space remains diversified and standards comparable to those that consolidated the sustainability and risk fields have yet to emerge.

Consensus in a scientific field is typically achieved when debates begin to cease [3]. The extent and intensity of these debates influence the pace at which consensus is established. It is challenging to definitively state whether we are converging or diverging in our understanding of resilience. This is largely due to the complex and multi-disciplinary nature of the field, which includes a large diversity of perspectives and approaches for the conceptualization and operationalization of resilience. Despite significant efforts to foster a shared understanding of resilience, promote interdisciplinary collaboration, and standardize methods and metrics, the trajectory towards consensus remains uncertain.

Several review works analyzing the concept of resilience have been studied to gain insights into the degree of consensus around resilience. A comprehensive review covering engineering systems' resilience from 2000 to 2015 by [34] shows that despite some similarities, there was no single, agreed-upon definition of resilience. [35] emphasized that not having a clear definition of resilience makes it difficult to apply the concept, especially in managing urban flooding. More recently, [36] observes that the idea of resilience is used differently in various fields of organizational resilience, leading to different understandings of the term. Similarly, [37] find that the conceptualization of resilience is diverse, with authors focusing on either the process (before, during, and after the adversity), the system capabilities, or the outcomes of a resilient organization. [38] also note inconsistent understanding of

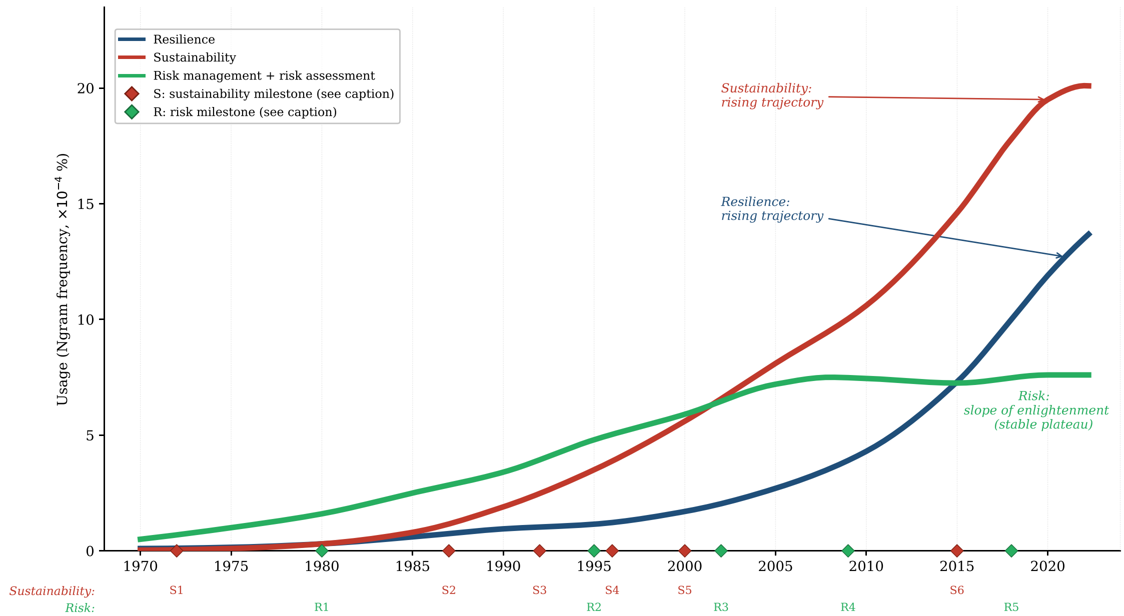

Fig. 4. Comparative evolution of the usage level of the concepts of resilience, sustainability, and risk.
Source: Google Books Ngram Viewer (1970–2022).

Table 2
Key milestones in the development of the sustainability and risk fields.

Sustainability milestones		Risk milestones	
S1	Stockholm Conference, UN Conference on the Human Environment (1972)	R1	Society for Risk Analysis founded (1980)
S2	Brundtland Report, *Our Common Future* [27]	R2	AS/NZS 4360 – Risk management standard [28]
S3	Rio Earth Summit, Agenda 21 (1992)	R3	NIST SP 800-30 – Risk assessment guide [29]
S4	ISO 14001 – Environmental management systems [30]	R4	ISO 31000 – Risk management principles [31]
S5	UN Millennium Development Goals (2000)	R5	ISO 31000:2018 update [32]
S6	Sustainable Development Goals, Paris Agreement [33]		

resilience in maritime contexts. Conversely, [39] note that despite some common understanding of resilience across different fields, misconceptions still persist, and [40] highlights a consensus on the definition of a resilient urban system while acknowledging a limited understanding of the resilience concept in socio-ecological-technological systems.

These statements show a certain level of disagreement at both the ontological and operational levels. However, this does not necessarily denote divergence; rather, it may reflect the context-specific nature of resilience. The challenge resides in identifying the extent to which these apparent disagreements are caused by either divergence in understanding or diversity of the operationalization approaches while maintaining a common understanding of the ontological definitions.

To explore further the distinction between convergence, divergence, and diversity, Table 3 presents a selection of resilience definitions from various literature sources over time. The listed papers are not intended to constitute an exhaustive corpus, but rather a representative sample drawn from the meta-reviews previously discussed, which synthesize the evolution of resilience concepts across multiple disciplinary domains.

A noteworthy trend observed is the shift from initial publications offering unique definitions to later works predominantly adopting established ones. This pattern suggests a movement towards convergence in the field.

The following observations can be derived from the information in the table;

1. The definitions marked with an asterisk in Table 3 primarily focus on operationalizing resilience. These definitions include specific metrics and performance indicators for evaluating resilience. For example, Haimes (2009) [47] incorporates costs and risks, while Nogal et al. (2016) [57] consider the level of service in their operational definitions. In contrast, the other definitions in the table are broader and more adaptable to various operational methods. These can be classified as ontological definitions.
2. Field/Domain: Different applications have led to the emergence of various domains of resilience, such as engineering, organizational, social, and economic resilience. Each domain often uses language and perspectives that are specifically tailored to its unique context. This diversification cannot be understood as divergence; instead, it reflects the adaptability of the resilience concept across diverse fields, rather than indicating a departure from the core principles of resilience.
3. Description of resilience: Although definitions of resilience in the domain of organizational resilience vary, often conceptualizing it as an outcome, a process, or an approach (Hillmann [36], there is a widely accepted consensus across various domains, which view resilience fundamentally as an 'ability'. Regardless of the specific context or application, the core idea of resilience as an ability to adapt, withstand, and recover remains consistently recognized.
4. Resilience of what: The operational definitions of resilience often specify the subject of resilience — typically 'systems' in engineering, 'communities' in the social domain, and 'organizations' in the organizational domain. These definitions are also commonly linked with the terms 'functionality' or 'operating state', as seen in the works of [60,61]. For instance, in more specific cases, resilience may refer to a particular firm or transportation network, with a focus on specific functionalities such

Table 3
Sample of definitions of resilience given by its components, chronologically sorted.

Year	Ref	Field/domain	Description	Of what	To what	Goal
2000	[41]	Social	ability	groups or communities	external stresses and disturbances	cope with
2004	[42]	Organizational	ability	firm	disruption	withstand and recover to its original or a more desirable state
2005*	[43]	Social	ability	community members	problem	take meaningful, deliberate, collective action to remedy the effect of, including the ability to interpret the environment, intervene, and move on
2005*	[44]	Economic	inherent ability and adaptive response	firms and regions	non-defined	avoid maximum potential losses
2006	[45]	Engineering	intrinsic ability	system	disturbance and unpredicted changes	adjust its functionality
2007	[46]	Organizational	ability	organization	strain, presence of adversity	absorb and improve functioning
2009*	[47]	Engineering	ability	system	major disruptions	withstand within acceptable degradation parameters, recover with a suitable time and reasonable costs and risks
2009	[48]	Engineering	ability	system	disruptive event	predict, absorb, adapt, and/or quickly recover
2009	[11]	Engineering	ability	system, community or society	hazard	absorb, accommodate to and recover from, in a timely and efficient manner, with preservation and restoration of its essential basic structures and functions
2010*	[49]	Engineering	ability	system	disruptive (set of) event(s)	reduce efficiently both the magnitude and duration of deviation from targeted system performance levels
2011	[50]	Engineering	ability	system	continuous and unpredictable change	absorb and maintain its vital functions
2011	[51]	Organizational	process	individuals	adversity, events, challenges or stress	exhibit a positive trajectory of entrepreneurial functioning
2012*	[52]	Economic	capacity	firms, industries, technologies, institutions	non indicated	reconfigure (i.e., adapt) its structure to maintain an acceptable growth path [..] over time
2013	[53]	Social	ability	community	disruptions or crises	function properly
2013	[54]	Engineering	intrinsic ability	system	(expected and unexpected) changes and disturbances	adjust functioning prior to, during, or after to sustain required operations
2013	[55]	Organizational	ability	system	actual or potential adverse events	prepare and plan for, absorb, recover from, or adapt to
2016	[56]	Social/Eng./ Organiz.	ability	system	errors, failures, environmental changes	retain basic functionalities
2016*	[57]	Engineering	ability	transportation network	disruptive events	absorb impact, maintain the level of service, or return to at least the same level of service within a reasonable time frame
2017	[58]	Organizational	process	actor (individual, organization or community)	adversity	adjust and maintains functioning
2020	[59]	Engineering	emergent property	infrastructure	vast range of disruptive events	withstand, respond and/or adapt by maintaining and/or enhancing its functionality

(*continued on next page*)

Table 3 (*continued*).

Year	Ref	Field/domain	Description	Of what	To what	Goal
2021	[60]	Organizational	ability	system	disaster	resist, adapt, and quickly return to its normal and stable operating state
2022	[61]	Engineering	intrinsic ability	system	changes and disturbances, major mishap or continuous stress	adjust its functioning and sustain required operations
2023	[38]	Organizational	ability	organization or segment	disruptive event	withstand and return to a desirable performance level
2023	[22]	Engineering	ability	system, community or society	hazards	resist, absorb, accommodate, adapt to, transform and recover [..] in a timely and efficient manner [..] essential basic structures and functions

as growth paths (e.g., [52]) or service level (e.g., [57]). This does not imply that different concepts are used for resilience. Instead, the resilience concepts are ontologically the same across different domains, and the definition is adapted to facilitate domain-specific operationalization.

5. Resilience to what: Although not specified in a few instances, the most recurring term is resilience to a disruptive event [59]. To some extent, other equivalent terms to disruptive events are adverse events [55] or crises [53]. A crisis is an extremely difficult or dangerous point in a situation, according to the Cambridge Dictionary. Recently, the notion of 'shock' has become more prevalent, e.g., [62,63]. Shocks refer to external short-term deviations from long-term trends that have substantial negative effects on the system [64]. In contrast, stress refers to the long-term trends or pressures that undermine the stability of a system and increase vulnerability within it [41,51]. [58] point out the severity level of the impact as a key area of divergence in definitions. Finally, some authors characterize disruptions as unpredicted, surprising, or unexpected [50].
6. The goal of resilience: The primary objective of resilience, as frequently cited in the literature, encompasses preparing and planning for, absorbing/withstanding/coping with, recovering from, and adapting to disruptions. Some definitions also specify that these goals should be achieved within a certain timeframe (e.g., [22]) or with minimal performance loss. Although not all reviewed literature includes these elements, none of the sources contradicts the overarching objective of resilience. Additionally, while the idea of recovery is commonly associated with resilience, there is often ambiguity about whether this recovery entails a return to a previous state of performance. This particular aspect has been discussed by [34]. [65] distinguishes between static and dynamic perspectives, usually associated with engineering and socio-ecological focuses, respectively. The static perspective assumes an optimal initial condition to be maintained and recovered, while the dynamic accepts multiple equilibria as the system evolves with or without an external disturbance.

The analysis of Table 3 reveals a notable consistency in the fundamental understanding of resilience, indicating a widespread consensus on its ontological definition across various domains. Operational definitions provide a more tailored description, leading to numerous variations of definitions. This observation aligns with [66] who noted that the diverse approaches to assessing resilience have prevented a unified operational definition. However, it is important to distinguish between diverse operational definitions, all aligned with the core concept of resilience while tailored to specific cases, and divergent operational definitions, in which the underlying conceptualization departs from the shared ontological interpretation, leading to incompatible framings of resilience across fields. For instance, [56,67] adopt a broadly consistent ontological understanding of resilience as the capacity of a networked system to withstand perturbations while retaining its core functionality. However, their operational definitions differ markedly. This contrast illustrates that ontological consensus does not automatically translate into operational uniformity, and that operationalization may diversify across domains and modeling traditions without necessarily implying conceptual divergence.

Recent works, e.g., [59,68], point out that there is no universal approach to operationalizing resilience. A consensual approach to operationalizing resilience would ideally include a widely accepted measure of resilience and universally recognized frameworks to assess it either qualitatively or quantitatively. An example of this high level of operational consensus is found in the area of risk assessment and management. Several standards and guidelines are widely used around the broadly accepted concept of *risk*. For example, ISO 31000 provides a framework for risk management, which applies to any type of organization, regardless of size, activity, or sector. Similarly, NIST SP 800-30 presents detailed guidelines for conducting risk assessments. It is widely used in information security and cybersecurity. Distinguishing between conceptual divergence and domain-specific diversification is not a trivial task, and requires both field-specific knowledge and in-depth analysis of how resilience is operationalized in practice. Further research is needed to establish criteria for differentiating legitimate contextual adaptations from incompatible conceptual departures, which is essential for any attempt to harmonize operational definitions of resilience.

Note that Table 3 is an illustrative synthesis rather than the product of a systematic review, and as such carries limitations. First, although the entries are drawn from meta-reviews that themselves rely on systematic sampling strategies, the specific definitions selected for inclusion in the table reflect an editorial choice intended to capture dominant conceptualizations across eras and domains, rather than the full distribution of definitions in the field. A different selection, drawn from the same meta-reviews or from additional ones, would alter the specific entries shown but, given the convergence already observed across the underlying meta-reviews, would be unlikely to change the qualitative pattern that motivates our analysis, namely, broad ontological consistency alongside operational diversification.

4. Barriers hindering scientific consensus on resilience

Resilience knowledge should eventually converge towards a common understanding on both the ontological and operational levels. However, the practical application of resilience often leads to, and benefits from, diversification of definitions, methods, and approaches. This diversity is needed to address the unique challenges and limitations inherent in different resilience domains and their respective system boundaries. The authors also find that there are a few cases where such diversification could potentially lead to divergence. Examples are provided where diversification is beneficial (e.g., *Operationalization of resilience* below) and where diversification might lead to divergence (e.g., *Resilience-context incompatibility*).

Scientific consensus can be significantly negatively influenced by internal factors, such as differing views and opinions of experts, as well as external factors, such as funding, political agendas, and personal biases. To describe such barriers to reaching a scientific consensus in the resilience field, this work draws on examples from the literature and inputs from resilience experts. This section presents examples of such barriers demonstrated by studies in the literature and feedback from resilience experts.

Literature-based barriers to resilience consensus

In this section, selected examples from prior research are presented to illustrate the diversification in resilience and the potential risk for divergence. The first example focuses on the misuse of the term resilience in contexts where it is not appropriate. The second example focuses on the diversification of operationalization of resilience, particularly in how it is applied to measure systems performance following disruptions.

Resilience-context incompatibility. The concept of resilience is closely related to other concepts relevant to the performance of complex systems such as vulnerability, reliability, and risk. In some cases, these concepts overlap. For example, several perspectives have been presented on the relationship between risk and resilience concepts at the fundamental level. One perspective considers that the two concepts are distinct, arguing that resilience considers recovery and adaptation while risk focuses on mitigation [69]. In this line, [68] note that risk focuses on the limit state in which the system fails, whereas resilience considers the process of degradation and recovery in system performance. Foundational issues were raised concerning these distinctions, and other researchers have advocated for resilience to be considered an integrated part of risk analysis [70,71]. Similar trends have appeared with other concepts and in specific sectors of complex systems. For example, a number of studies on the power grid consider that resilience is a necessary component of reliability [72] while other studies call for a clear distinction between resilience and reliability [73]. Recent studies focusing on transportation systems acknowledge that there is a clear conceptual distinction between resilience and other concepts such as vulnerability (i.e., considered as different states of complex systems) and have found that these concepts become more ambiguous at the operational level [74]. The disagreement in the conceptual understanding and application of resilience in prior studies highlights the potential risk of using resilience outside of its context. For example, referring to 'resilience' when in fact what is being evaluated is the robustness or vulnerability of a system is problematic and further contributes to divergence in the research field of resilience.

Operationalization of resilience. The operationalization of resilience has recently garnered attention and raised questions about the potential applicability of resilience definitions and methods in practice. Some studies distinguish between the concept of resilience and its operationalization and refer to the '*resilience metrics*, which measure the systems' ability to prepare for and resist the unexpected hazards, absorb their effects, maintain desired functionality and rapidly recover' [75]. With this approach, the authors appreciate the dichotomy between ontology and operationalization, by indicating what the metrics measure and avoiding the definition of resilience. In the context of critical infrastructure, the resilience concept has been used to measure the system's performance in response to disasters. For example, the performance of transportation systems is often evaluated as a function of the number of roads reopening, the traffic flow, or the overall connectivity of the network [76]. Re-framing the concept of resilience in terms of the provision of essential services would consider the resilience of transportation systems to be a function of accessibility to critical facilities such as supermarkets, shelters, and healthcare facilities [77]. While the concept of resilience can be universal, its operationalization is different due to the difference in the system definition and objective functions. Operationalizing the resilience of transportation systems then requires the consideration of systems, functions, and services that lie outside the physical definition and boundary of a transportation network. It also requires a different definition and conceptualization of resilience than the one that only considers the functionality of the infrastructure alone. The existing diversification in the operationalization of resilience is actually essential because it allows the incorporation of aspects that are only relevant to specific systems as well as the consideration of multiple perspectives.

Expert perspectives on resilience barriers

To better understand the state of resilience research and practice, input from resilience experts was drawn through a workshop that brought together participants from academia. The goal of the workshop was to identify achievements, needs, and challenges in the field of resilience to determine pressing issues and research priorities. Based on the synthesis of the inputs from the workshop participants, we have identified resilience aspects across different stages of ontological and operational progression from convergence to diversification and potential divergence.

The workshop, titled 'Resilience: feedback, feedup, and feedforward', was organized as part of the annual meeting of the 4TU-Resilience Engineering community in the Netherlands in November 2022. While the selection of participants was not controlled, the participants who signed up for the workshop were all attendees of the community meeting and had experience in resilience research or practice. Specifically, the workshop brought together a group of experts with varied levels of experience ranging from 2 to 15 years and different fields of expertise including engineering, social sciences, and natural sciences.

The workshop was not intended to be a formal elicitation of knowledge or a mechanism to draw insights from a population, but rather an exercise with stakeholders interested and invested in resilience research to explore important issues and research challenges that need to be addressed in the next generation of resilience research. Through the workshop activities and participants' responses to discussion questions, the authors have identified four main barriers to resilience research described below.

Terminology. The participants perceive that there is a lack of common terminology and understanding of resilience, and no consensus on whether resilience terminology should be general to enable cross-cutting disciplines or specific. The authors believe that such an outcome is mostly the result of diversification in the ontological definition as well as diversification in the language used across different domains and disciplines that employ the concept of resilience. However, when disagreement occurs in the ontology or the general concept and principle of resilience, then there is concern about potential divergence. This barrier is also evidenced by recent trends in the literature [71].

Ownership and governance. There is a notable trend of increasing popularity and importance of resilience and pressure to apply it in practice across different sectors. However, the limited knowledge and expertise of resilience among practitioners makes it difficult to implement resilience concepts. There is also no clear understanding regarding the responsibility for building and improving resilience, which makes it difficult to translate priorities into research agendas. Who is responsible for managing and improving resilience? It is unclear whether the role of resilience management falls under the direction of policymakers or community members.

System definition. Defining a complex system and its boundaries is dependent on specific domains, which results in diverse temporal and spatial scales of resilience measurement and evaluation. This results in a trade-off between breadth and depth, which is also different across different systems. While this may present itself as a case of diversification, it can become a barrier to convergence if disciplinary researchers do not properly communicate the process for defining boundaries across heterogeneous systems, leading to divergence in system definition for resilience assessment.

Information and knowledge. The lack of data and/or the poor existing data-sharing standards can be a barrier to achieving a common understanding of resilience, as scholars might be compelled to focus on specific aspects due to data limitations. The issue of data and information gathering and sharing emerged as a significant point of discussion at the workshop, with a range of views and perspectives. On one hand, there was a clear emphasis on the need to collect data and ensure its integration across systems. Contrarily, some participants noted that sufficient data already exists, but the pressing requirement is for this data to be shared and standardized across various sectors.

5. Risks & opportunities for convergence and divergence

5.1. The role of convergence and divergence

Reaching a unified understanding of resilience is a complex process, presenting both opportunities and challenges alike. This process is not unique to resilience but is characteristic of any scientific field seeking to develop a comprehensive and shared understanding of a concept. During this process, we encounter phases of convergence, where diverse ideas and theories merge, and divergence, where new perspectives and differences in interpretation drive the field to expand in different, sometimes contradictory, directions. These phases of convergence and divergence, while seemingly contradictory, are integral aspects of scientific progress. Each phase brings with it distinct implications for the future of resilience research and practice. Convergence can encourage interdisciplinary collaboration, standardize methods and metrics, and foster the development of shared tools and data sets. However, it can also risk oversimplification of complex concepts and practices. Divergence, especially in the early stage of concept formation, can catalyze innovation and broaden our understanding of the concept across various contexts, but it may risk leading to a permanent divergence if the diverse definitions and methods do not agree on the general concepts and ontology of resilience. Therefore, the balance between convergence and divergence is critical in exploring the opportunities and challenges on the path towards a unified understanding of resilience.

It is important to recognize that divergence plays distinct and valuable roles at different stages of a field's development. Beyond its acknowledged contribution to early concept formation, divergence continues to foster innovation through the emergence of competing methodological approaches and conceptual frameworks. In the field of resilience, productive divergence is observable in the ongoing dialogue between engineering-focused approaches, which emphasize system functionality and recovery metrics, and socio-ecological perspectives, which prioritize adaptive capacity and transformation. Rather than conflicting paradigms, these competing frameworks complement each other, each illuminating different aspects of resilience and collectively enriching the field's understanding. This competition stimulates methodological innovation, reveals underlying assumptions, and contributes to a more robust and comprehensive understanding of the concept.

However, the constructive nature of divergence must be distinguished from uncontrolled fragmentation. Excessive divergence , characterized by fundamental disagreements on basic concepts or the proliferation of incompatible frameworks, can hinder the consolidation of the field and impede practical application. The challenge, therefore, lies not in eliminating divergence but in fostering conditions where divergence drives innovation while preserving the conceptual coherence necessary for building cumulative knowledge.

5.2. Balancing exploration and exploitation

The transition towards convergence should be seen as a balance between exploration and exploitation. Exploration involves investigating new ideas and perspectives, while exploitation involves consolidating existing knowledge and applying it in practice. Balancing these two aspects is crucial for the effective transition towards convergence in understanding and applying resilience. Various examples can be drawn that demonstrate the significance of this equilibrium:

Exploration: extensive exploration could lead to a divergence of perspectives. For example, the wide-ranging exploration of resilience definitions is an example of an extensive exploration where every scholar proposed their own definition. This can lead to divergence if not balanced with practical applications and consolidation of ideas. On the other hand, limited exploration could lead to fragmentation. Areas like the human dimension in the built environment require more exploration. The lack of exploration in this area can lead to fragmentation and disconnect from current research trends.

Exploitation: overemphasis on exploitation without sufficient exploration can lead to premature convergence, limiting the depth and breadth of understanding resilience. On the other hand, limited exploitation can widen the gap between theoretical knowledge and application. This is particularly evident in the disparity in knowledge distribution from well-explored theory to less developed applications in the resilience field. For instance, while substantial theoretical work exists (e.g., resilience assessment frameworks, resilience optimization techniques, etc.), there is often a noticeable gap in effectively translating these theoretical works into practical applications. This gap can be observed in fields such as disaster management, where despite extensive theoretical knowledge, real-world disaster response efforts sometimes struggle to effectively utilize these theoretical works. Here, it is worth noting that education plays a pivotal role in bridging the gap between theory and its application. Education equips the current generation, who are future professionals, with the skills and knowledge needed to apply theoretical concepts of resilience in practical situations.

5.3. Implications for research and education

In research, convergence aids in simplifying the operationalization of resilience by promoting a uniform understanding and facilitating effective communication. However, early convergence comes with its own risks, especially considering the context-specific nature of resilience. A major concern is oversimplification, where a too-standardized definition may not fully capture the diverse and context-dependent aspects of resilience. This could limit how effectively resilience concepts are applied across different systems. Additionally, a narrow definition might exclude certain stakeholder perspectives, which are crucial for a comprehensive understanding and effective application of resilience.

Divergence, despite its role in fostering diverse perspectives, especially in the early stage of field formation, introduces challenges in resilience education. The vast array of interpretations complicates the delivery of comprehensive and coherent instruction, potentially leading to confusion and misunderstandings among students and practitioners, and hindering practical applications. Moreover, divergence could spawn inconsistencies in resilience curricula across educational institutions. It may further complicate the creation of standardized teaching materials and the development of interdisciplinary courses. Therefore, seeking a balance between upholding diverse perspectives and establishing a unified teaching framework is crucial to successful resilience education.

6. Moving forward: a call for pragmatic action

Much progress has been made towards a common understanding of resilience, yet there is still a long way to go in reaching a significant degree of scientific consensus. Ongoing research and collaboration among stakeholders (i.e., researchers, practitioners, and policymakers) play a crucial role in advancing our understanding of resilience and promoting convergence. Such collaboration facilitates the translation of theoretical knowledge into practical applications, effectively narrowing the gap between research (the knowledge forefront) and real-world implementation (the tail). Researchers can provide the latest findings and theories, practitioners can offer insights into on-the-ground challenges and applications, and policymakers can help shape these insights into actionable strategies and policies.

To achieve a significant degree of scientific consensus in the field of resilience, it is important to push for an intentional research agenda that addresses key gaps and challenges. This requires identifying and eliminating sources of noise that hinder the achievement of scientific consensus, such as conflicting interests, biases, and divergent interpretations. By actively addressing these barriers, researchers and stakeholders can achieve a more unified and comprehensive understanding of resilience, driving progress in research and practice.

It is important to approach the process of scientific consensus in resilience research with caution, pragmatism, and awareness of the inherent complexity and diversity of the concept. A significant degree of consensus may not be immediately attainable and, in certain situations, it may not even be the most beneficial route. Instead, a dynamic and iterative approach is needed, continuously revising and refining our understanding based on emerging evidence and insights. The following recommendations could facilitate achieving scientific consensus in the field of resilience:

- Developing a common language: to avoid misunderstandings and facilitate communication, it is important to establish a shared language for resilience that is universally understood and adopted.
- Conducting more up-to-date systematic reviews: systematic reviews can help identify and synthesize existing knowledge on resilience, highlighting areas where agreement and disagreement exist.
- Conduct an empirical assessment of resilience consensus to guide research priorities. Examples include examining quantitatively the evolution of resilience research across publications, collaborations, and flow of new knowledge within the scientific community, among others.
- Facilitating open communication: regular meetings and open forums can be organized to promote transparency and encourage

the exchange of ideas and feedback between researchers and practitioners.

- Development of consensus-building mechanisms: establish mechanisms for building consensus, such as workshops, conferences, and specialized journals, to facilitate ongoing dialogue and collaboration.
- Forming a multidisciplinary community: bring together experts from different fields, such as psychology, sociology, engineering, and environmental science, to collaborate on defining and measuring resilience.
- Engaging research leaders to drive consensus: Research leaders should actively collaborate and seek alignment within their areas of expertise, which can significantly contribute to consensus-building by streamlining research efforts.

7. Concluding remarks

This paper critically examines the current state of scientific consensus in the multidisciplinary field of resilience. As an area of increasing importance across various domains, resilience faces complex challenges due to the diversity of definitions, perspectives, and approaches. The primary objective of this analysis is to ascertain whether the field is converging towards a common understanding of resilience or diverging into disparate interpretations. While divergence is beneficial and contributes to the expansion of the field at the beginning, the scientific community must reach a shared understanding of the concept of resilience to enable its research progress as well as its implementation in practice. In the case of resilience research, a key finding of this study is that the scientific consensus is not only a function of convergence and divergence but also diversification. The distinction between divergence and diversification is crucial to the progress of resilience research whereby variations of definitions and methods are unavoidable and help advance resilience across heterogeneous domains while maintaining fidelity to the essential elements that define resilience. This work shows that both divergence and diversification play valuable roles in the early stages of a field's development. However, as the field of resilience evolves, the process of transitioning towards convergence in resilience requires a careful balance between exploration of new ideas and exploitation of existing knowledge. The effective integration of exploration and exploitation that is supported by the education of future generations is essential to translate resilience theory into practical applications. By examining the literature and consulting with experts, this study identifies potential barriers that hinder scientific consensus on resilience which highlight important issues of incompatibility and overlap across closely related concepts (resilience, risk, reliability), operationalization of resilience, and lack of data sharing standards, among others. As a result, the outcome of this analysis calls for the resilience community to carefully think and strategically plan the future trajectory of resilience research to achieve consensus in a way that advances science and benefits society. Achieving such consensus would benefit from empirical evidence of specific causal factors that drive barriers to resilience consensus.

CRediT authorship contribution statement

Maria Nogal: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Omar Kammouh:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Hiba Baroud:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

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Data availability

The authors declare that the data supporting the findings of this study are available within the paper.

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