

Climate change risks on railway infrastructure: A systematic review and analysis

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ABSTRACT

As critical infrastructure, railways are highly vulnerable to climate hazards intensified by climate change. However, awareness of these risks is low, and comprehensive studies outlining these hazards and their impacts on railways are also scarce. To address these gaps, this review aims to identify climate-related risks, clarify the hazard-impact relationships and risk interconnections, and explore strategies to account for the influence of climate change on these risks. To this end, a systematic literature review was conducted in two stages. First, 71 peer-reviewed papers were collected through developing search strings, applying inclusion/exclusion criteria, and performing backward/forward citation searches. Second, the required information was systematically extracted from the papers and critically analyzed to address the research objectives. As a result, 24 climate hazards and 29 associated impacts were identified and categorized. The hazards and impacts having the most and least occurrence in the literature were also highlighted. Informative matrices were developed to correlate hazards with impacts and illustrate the cascading effects of the impacts. Four distinct approaches used to address the effects of climate change on climate risks were identified and critically discussed. The study also highlights critical gaps in the literature to guide future research.

1. Introduction

Railways are sustainable, cost-effective, and efficient modes of transportation, offering safe and reliable transit for passengers and goods. They can move large volumes of freight/people over long distances with lower carbon emissions than other transport modes. Therefore, railway networks play a crucial role in global transportation (Kendra et al., 2023; Mulley et al., 2017; Shah et al., 2021).

Railway networks are highly vulnerable to climate hazards, such as high temperatures, heatwaves, heavy rainfall, snowfall, flooding, and extreme winds, due to their linear nature (Torvanger et al., 2024). These networks often pass through diverse geographical regions, exposing them to various localized climate hazards. Moreover, many railways were designed and constructed based on historical climate conditions

and existing hazards (Torvanger et al., 2024). However, climate change is increasing the likelihood of these hazards exceeding the design thresholds, which can inflict increased damage to rail infrastructure (IPCC, 2023; Mishra & Sadhu, 2023; Salimi & Al-Ghamdi, 2020).

Generally, climate hazards can result in several adverse impacts, including track buckling, landslides, flooding, track washouts, operational disruptions, increased maintenance demands, and various other challenges (see Table A1). These impacts significantly reduce availability, punctuality, and safety while increasing operation and maintenance (O&M) costs (Garmabaki et al., 2022; Pour et al., 2020; K. Soleimani-Chamkhorami et al., 2024; Sun et al., 2022). For instance, it was found that climate hazards (e.g., snowfall, abnormal temperatures, icing events, and extreme winds) account for 5 to 10 % of total failures (i.e., climatic and non-climatic) and up to 60 % of interruption events in

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the Swedish railway network (Garmabaki et al., 2021; Thaduri et al., 2021).

Recent studies have examined how climate change intensifies climate-related risks to railway networks. Kasraei et al. (2024) applied statistical and machine learning methods to analyze the effects of variations in climate variables, including temperature, precipitation, humidity, and wind speed, on climate-related failures in railway assets. They claimed that an increase in precipitation from 0 to 1.25 mm/hr in certain regions of Sweden could reduce the mean time between failures (MTBF) by approximately 60 %. Liu et al. (2021) used a machine-learning model to assess the susceptibility of Chinese railway infrastructure to extreme precipitation. They projected that under global warming of 1.5 °C and 3 °C, the proportion of highly susceptible railway infrastructure would increase by 2.8 and 6.7 times, respectively, compared to the baseline period of 1981–1998. Consequently, limiting warming to 1.5 °C could save approximately \$2.06 billion annually in economic losses, including direct damage and repair costs, compared to 3 °C. Soleimani-Chamkhorami et al. (2024) utilized a proportional hazard model to analyze the impact of climate change on the maintenance actions for railway assets. Their findings suggest that the life cycle cost (LCC) could increase by approximately 11 % under future climate scenarios compared to current climate conditions. Chinowsky et al. (2019) assessed future delay minutes resulting from speed limitation policies implemented to mitigate the risk of rail buckling under high-temperature conditions. Their projections indicate significant increases in delay minutes for the U.S. rail network, resulting in cumulative costs of \$25–\$60 billion by 2100, depending on the emissions scenario.

According to the literature, the impacts of climate hazards on railway infrastructure are growing due to climate change. However, surveys revealed a low level of awareness of these issues even among railway managers and stakeholders (Garmabaki et al., 2021). Moreover, there is a noticeable lack of comprehensive studies that clearly outline climate hazards and their associated impacts on railway systems. To bridge these gaps, a systematic literature review and critical analysis were conducted, aiming to:

- Identify and categorize climate hazards and their related impacts on railway infrastructure.
- Identify the climate risks and geographic regions that have been extensively studied or remain underexplored.
- Understand hazard-impact relationships, risk interconnections, and cascading effects.
- Explore approaches for addressing the impacts of climate change on climate risks.
- Highlight research trends and gaps to guide future studies.

The results present a systematic risk identification process, offer valuable insights into current challenges for railway stakeholders, serve as a foundational resource for risk managers, and offer foresight into future research directions to advance climate risk management for railway infrastructure.

2. Background

2.1. Climate hazards and climate change

Climate hazards refer to the potentially harmful events, trends, or conditions related to climate and weather that pose risks to human health, ecosystems, infrastructure, and economies (IPCC, 2022). Examples include extreme temperatures, heatwaves, heavy rainfall or snowfall, lack of precipitation, strong wind, and other extreme events. Such events occur when climate variables (e.g., temperature and precipitation) exceed thresholds near the upper or lower ends of their observed ranges (IPCC, 2013). These events can also lead to compound events like snowstorms and/or cascading hazards like flooding (see Section 4.2.1)

(Gustafsson et al., 2023). Climate hazards also include gradual changes in climate properties, such as rising sea levels and shifting in groundwater levels (IPCC, 2022).

Climate change alters the statistical properties of the climate system, leading to changes in the frequency, intensity, and duration of climate hazards (IPCC, 2021). Consequently, projecting future climate conditions is essential for assessing and understanding potential future climate hazards (Palin et al., 2021; Torvanger et al., 2024).

Future climate projections are typically generated by simulating the climate system using climate models. The Coupled Model Intercomparison Project (CMIP), organized by the World Climate Research Programme (WCRP), is a significant initiative that coordinates the efforts of climate modeling groups worldwide. The latest and most widely used phases of this project are the fifth and sixth phases, known as CMIP5 (Taylor et al., 2012) and CMIP6 (Eyring et al., 2016; O'Neill et al., 2016). Climate projections rely on scenarios of greenhouse gas (GHG) emissions, concentrations, radiative forcing, aerosols, and land use changes. These scenarios are based on a range of assumptions about future socioeconomic and technological developments, which may or may not be realized. Consequently, a variety of climate scenarios have been proposed in scientific literature to account for these different assumptions and to provide a comprehensive range of potential future climates (IPCC, 2013, 2021, 2022).

The Representative Concentration Pathways (RCPs) are one of the most well-known climate scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC) (Bienvenido-Huertas et al., 2021). Four main RCP scenarios include RCP2.6, RCP 4.5, RCP6.0, and RCP8.5 (IPCC, 2013; O'Neill et al., 2016). To consider potential future socioeconomic conditions in RCPs, the IPCC proposed Shared Socio-Economic Pathways (SSPs) (IPCC, 2021; O'Neill et al., 2016; O'Neill et al., 2014; Wang et al., 2023).

2.2. Climate-induced impacts on railway

Railway infrastructure is a complex transportation network composed of numerous interconnected elements, including tracks, structures (such as bridges, viaducts, and tunnels), rolling stock, power supplies, signaling systems, and communication equipment (Taylor, 2020). Given the extensive range of components within railway infrastructure, this study focuses on the critical assets of tracks, including rails, fasteners, sleepers, ballast, sub-ballast, and switches and crossings (Indraratna et al., 2011; Satish & Agarwal, 2013).

Climate hazards can lead to a wide range of impacts on railway infrastructure and operations. Fig. 1 illustrates several climate-related incidents that have impacted rail infrastructure. In March 2023, heavy rainfall and snowmelt caused flooding on a track in Western Sweden, leading to service disruptions between Varberg and Borås, as shown in Fig. 1a (Karlsson & Moran, 2023). In October 2019, flooding washed away sections of the track between Abergavenny and Hereford (Fig. 1b) (NetworkRail, 2019). In January 2023, a landslide near Hook station in Hampshire severely damaged the track, as depicted in Fig. 1c (Haughey, 2023). In August 2020, debris carried by flooding obstructed the track near Carmont, Aberdeenshire, leading to a passenger train derailment (Fig. 1d) (Branch, 2021). Fig. 1e illustrates lateral track buckling in Sweden during the summer of 2020 due to high temperatures (Trafikverket, 2022). Additionally, the Malmbanan railway, essential for iron ore transport between Kiruna in Sweden and Narvik in Norway, experienced two derailments in 2023 and early 2024, likely due to heavy snowfall and extreme cold, as shown in Fig. 1f (Bacić, 2024).

In addition to the above impacts, climate hazards can also cause various delays, service disruptions, and many other undesirable operational incidences (Garmabaki et al., 2021; Sun et al., 2022). Therefore, climate-related impacts on railway networks can be categorized into two main types, physical and operational impacts. Physical impacts involve direct damage to railway infrastructure, such as track buckling and landslides, while operational impacts encompass service disruptions,

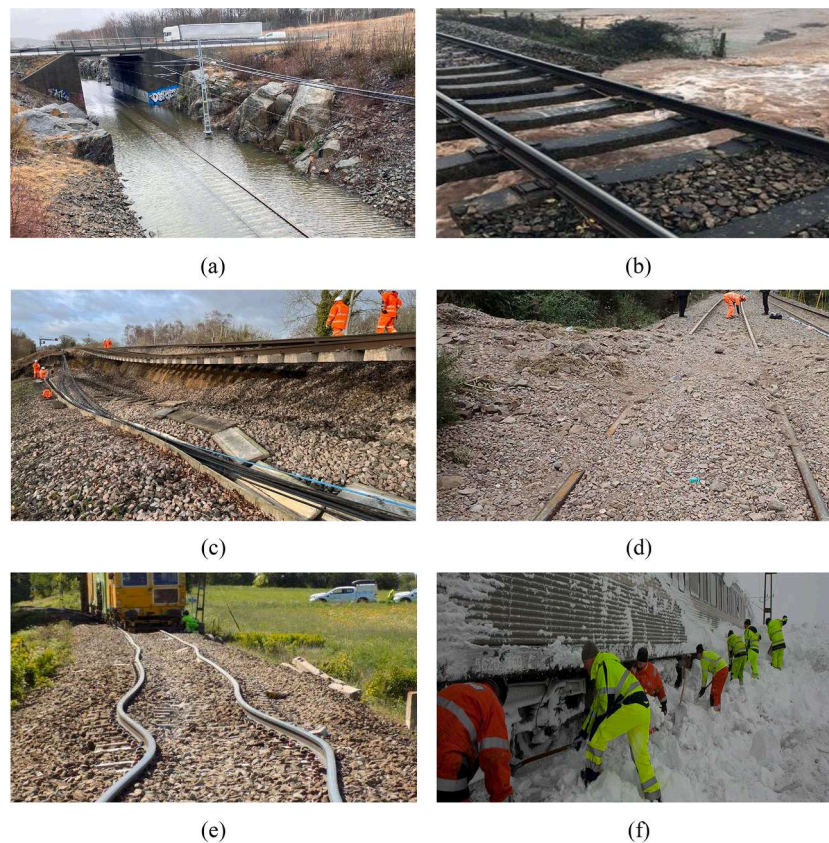


Fig. 1. Examples of climate-related impacts on railway transportation: (a) flooded track (Karlsson & Moran, 2023), (b) track washaway (NetworkRail, 2019), (c) track landslide (Haughey, 2023; NetworkRail, 2024), (d) debris on track (Branch, 2021), (e) rail buckling (Trafikverket, 2022), and (f) derailment in cold weather (Soleimani-Chamkhorami et al., 2024).

delays, maintenance disruptions, and safety risks. Moreover, physical impacts can also lead to subsequent operational impacts and necessitate additional maintenance. Thus, understanding the interconnections and cascading effects of these impacts is crucial for effective climate risk assessments (see Sections 4.3 and 4.4).

2.3. Climate change risk management

Risk is the effect of uncertainty on objectives (IEC 31010, 2019), encompassing potential adverse consequences for human or ecological systems. These consequences can affect lives, health, well-being, economic, social and cultural assets, infrastructure, services, ecosystems, and species (IPCC, 2022). In the context of this study, risk refers specifically to the potential adverse impacts of climate hazards on railway infrastructure, operation, and maintenance.

Traditionally, risk can be quantified by multiplying the probability of its occurrence by the severity of its consequences (Aven, 2015; Rausand, 2013). This definition of risk is applicable in a stationary situation that faces challenges in the context of climate change. While estimating probabilities of extreme weather events is feasible, establishing a direct link with consequences is complex (Palin et al., 2021). To tackle this issue, IPCC defines risk as a function of dynamic interactions between climate hazards with the exposure and vulnerability of the affected human, ecological system, and infrastructure (IPCC, 2022). Exposure refers to the presence of people, livelihoods, ecosystems, infrastructure, etc. in locations that could be negatively impacted. It means that exposure depends on time and place. Vulnerability indicates the propensity or predisposition to be adversely affected which can be determined by sensitivity or susceptibility to harm and the lack of capacity to cope and adapt. The magnitude and likelihood of hazards, exposure, and vulnerability can be uncertain and may change over time and across

different geographical areas due to socio-economic shifts and human decisions (IPCC, 2022).

Climate risk management process involves establishing the scope, context, and criteria, as well as identifying, analyzing, and evaluating risks. The evaluation leads to decide whether to accept, avoid, or control risks to an acceptable level, considering the costs and benefits of actions taken. The process is also followed by coordinated efforts to minimize, monitor, and control the probability and impact of unfortunate events (IEC 31010, 2019; Rausand, 2013). A possible climate-related risk management process by incorporating IPCC guidelines into the ISO 31000 framework is illustrated in Fig. 2.

Climate change can affect climate risks by changing the frequency, intensity, and distribution of climate hazards. As a result, climate risk assessments should consider potential changes in risk levels over time (IPCC, 2022). This approach enables a comprehensive evaluation of asset vulnerabilities under projected future climate conditions. A detailed discussion of this issue is provided in Section 4.5.

It should be noted that in this paper, we define climate change risks as climate risks influenced by climate change, based on the reviewed literature. For simplicity, we refer to them as climate risks.

3. Methodology

This study conducted a systematic literature review to collect, identify, and critically analyze relevant literature. The approach follows a structured and replicable process to ensure transparency, reduce bias, and produce reliable results (Carrera-Rivera et al., 2022; Page et al., 2021). In this regard, a set of search string was developed and updated throughout the review process to effectively identify relevant studies. Inclusion and exclusion criteria were applied to refine the initial dataset, ensuring relevance to the research objectives. Additionally, backward

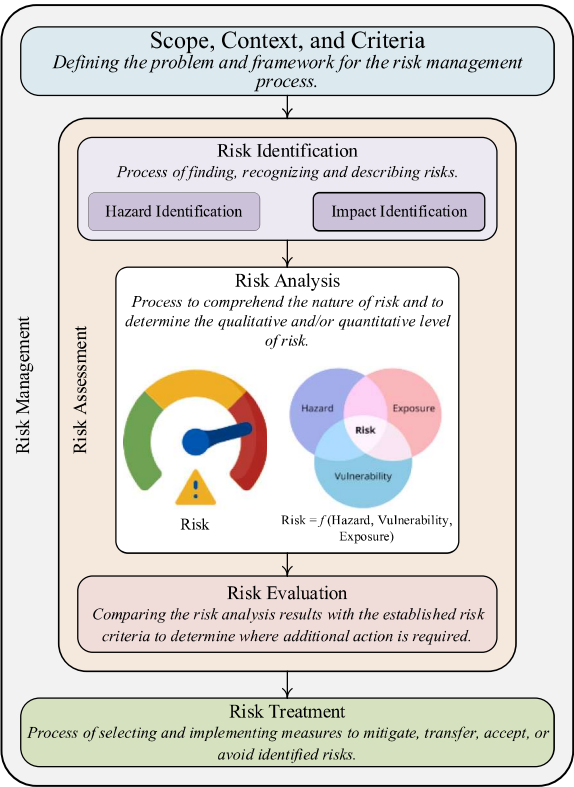


Fig. 2. Climate risk management process by incorporating IPCC guidelines (IPCC, 2022) to ISO 31000 framework (IEC 31010, 2019).

and forward citation searches were conducted to identify related studies that may not have been captured in the initial search (Sheikhhoshkar et al., 2023).

Subsequently, key information from the papers was systematically extracted and organized into a structured table (Carrera-Rivera et al., 2022; Lagap & Ghaffarian, 2024). The extracted data were then critically analyzed and categorized to achieve the research objectives.

This explicit and structured process ensures efficiency in producing reliable results (Carrera-Rivera et al., 2022; Page et al., 2021). The efficiency has been justified in previous studies on various topics such as climate change impacts on transportation systems (T. Wang et al., 2020) digital risk management twinning (Lagap & Ghaffarian, 2024), and other areas (Banihashemi et al., 2023; Mishra & Sadhu, 2023; Sheikhhoshkar et al., 2024). The detailed methodology is outlined in the following subsections.

3.1. Paper collection

The Web of Science (WoS) and Scopus digital libraries were chosen for conducting search. These databases are among the leading multi-disciplinary resources, providing content from numerous active, peer-reviewed journals (Banihashemi et al., 2023; Carrera-Rivera et al., 2022; Lagap & Ghaffarian, 2024; Sheikhhoshkar et al., 2024).

To develop the search string, *climate change*, *railway*, and

Table 1

Final search query.

Digital library	Combined search terms
Scopus & Web of Science	("Climate Change" OR "Climate Hazards" OR "Global Warming" OR "Extreme Weather Events") AND ("Railway" OR "Railroad" OR "Rail") AND ("Infrastructure" OR "Track" OR "Asset" OR "Rail" OR "Sleeper" OR "Tie" OR "Ballast" OR "Switches and Crossings" OR "Turnouts")

infrastructure were chosen as the main keywords, grouped with their synonyms into three sets. The finalized search query, as presented in Table 1, was entered into the search fields of the two digital libraries. At this stage, the query was applied to the Title, Abstract, and Keywords of documents, resulting in a total of 1,766 papers, as shown in Fig. 3.

Four distinct inclusion and exclusion criteria were defined as presented in Table 2. By applying these criteria and removing duplicates, the sample was reduced to 65 publications (Fig. 3). Notably, no constraints were imposed on the timeframe for data collection, encompassing all records accessible.

To minimize the risk of overlooking important literature, backward and forward citation searches were also conducted (Gusenbauer & Haddaway, 2020; Jalali & Wohlin, 2012). Through this manual search, we identified and incorporated 6 additional papers into the final dataset. Following this systematic process and eligibility assessment, 71 peer-reviewed papers were approved for detailed data extraction and content analysis, as presented in Table A1 of the Appendix.

3.2. Data extraction and content analysis

The collected papers were thoroughly reviewed to extract the required information. Key data points, including the year of publication, geographical location, research objectives, climate hazards and impacts under investigation, key findings, and approaches used to address climate change, were organized into a structured table (e.g., Table A1). The extraction process was conducted by the first author, reviewed by the second author, and validated by the remaining authors to ensure accuracy and consistency (Sheikhhoshkar et al., 2024).

The final step of the review involved synthesizing and analyzing the extracted data to achieve the research objectives (Lagap & Ghaffarian, 2024). Some objectives, such as identifying the geographical distribution of publications, identifying climate hazards and impacts, and highlighting risks that received the most or least attention, were addressed through direct analysis of the extracted data. However, deeper critical analysis and collaborative brainstorming sessions among the authors were conducted to achieve other objectives (Sheikhhoshkar et al., 2023; Wang et al., 2020).

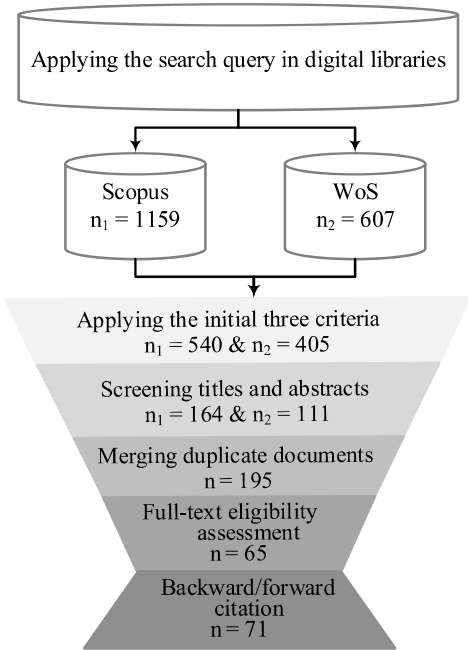


Fig. 3. Resource selection process.

Table 2
Applied inclusion and exclusion criteria.

Criterion type	Inclusion criteria	Exclusion criteria	Implementation of criteria
Document type	Peer-reviewed journal articles	Conference papers, book chapters, and other grey literature such as reports and theses	Applying automation filter of digital libraries
Field of research	Engineering and Science	Other fields	Applying automation filter of digital libraries
Language	Written in English	Written in a different language from English	Applying automation filter of digital libraries
Relevance to research goals	Considering climate change and related climate hazards Focusing on the selected railway infrastructure	Others	Screening title and abstract by Authors Assessing full text by Authors

4. Results and discussions

4.1. Yearly and geographical distribution of the papers

Fig. 4 illustrates the annual distribution of selected publications from 2007 to 2024. The initial publications in 2007, coupled with the limited number of early studies, indicate that this is an emerging research area. Moreover, the upward trend in the number of papers over the years underscores growing interest and expanding research efforts in this domain.

The country distribution of the selected papers is depicted in Fig. 5. It reveals the participation of 22 distinct countries. The figure also shows a prominent contribution from the UK, leading with 22 papers. China follows with 12 papers, while Sweden, the USA, and Germany contribute 6, 4, and 4 papers respectively. Several other countries, including Spain, Austria, Korea, and Canada, and many others, have made contributions in this field, highlighting a diverse but relatively growing international interest in this emerging research area.

4.2. Climate risk identification

Risk identification, in this paper, refers to the systematic identification of climate hazards and their related impacts on railway tracks and operations. This process should be thorough and complete (Aven, 2015; IEC 31010, 2019; Raspotnig & Opdahl, 2013; Rausand, 2013). Therefore, during the review of the collected papers, all identified climate hazards and impacts were extracted, regardless of their intensity, likelihood, or geographical variations. The identified hazards and their

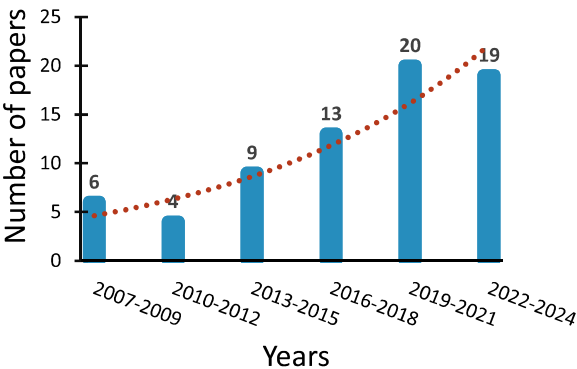


Fig. 4. Yearly distribution of the selected papers.

induced physical and operational impacts on railways are detailed in the following subsections.

4.2.1. Climate hazard identification

During this study, 24 climate hazards were identified and presented in Table 3. As observed, these hazards can be categorized into primary and secondary climate hazards. Primary hazards refer to first-order weather conditions that directly arise from anomalies or extremes in climate variables, such as higher mean temperatures or heavy rainfall. Secondary hazards arise either from the cascading effects of primary hazards (e.g., flooding caused by heavy rainfall) or from the interaction or combination of multiple primary hazards (e.g., snowstorms combining extreme winds and snow). In this classification, we grouped cascading and compound hazards together as secondary hazards since both originate from primary hazards. The relationships between climate variables, primary climate hazards, and secondary climate hazards are depicted in Fig. 6. This diagram shows how climate variables lead to primary hazards, and how the interaction of primary hazards can lead to secondary hazards.

This categorization highlights the multifaceted and hierarchical nature of climate hazards and assists risk managers in accounting for the compounded and cascading effects of such hazards. For instance, when assessing the risks of heavy rainfall in a specific location, there is a potential risk of flooding as a cascading effect in downstream or adjacent areas.

The identified climate hazards were prioritized based on the significance and emphasis given in the literature. To achieve this, the number of times each hazard was addressed in the reviewed papers was calculated. Collectively, these hazards were mentioned a total of 188 times across the 71 reviewed studies. The ten climate hazards receiving the most attention in the literature are presented in Fig. 7a. These include heavy rainfall, higher mean temperatures, flooding (pluvial, fluvial), extreme winds, storms, higher sea levels, heatwaves, changes in groundwater levels, heavy snowfall, drought, heavy snowfall, and changes in humidity. This analysis highlights the hazards that have been frequently studied and those that remain underexplored.

Moreover, the contribution of each climate variable to the identified climate hazards is illustrated in Fig. 7b. As shown, precipitation, temperature, wind, sea level rise, and humidity account for 37.4 %, 36.6 %, 12.2 %, 8.9 %, and 4.9 % of the total climate hazards, respectively. This highlights the predominant role of extreme precipitation, temperature variations, and wind in driving climate hazards.

4.2.2. Climate impact identification

As mentioned above, the identified climate impacts on railway networks are categorized into physical and operational.

4.2.2.1. Physical impacts. In this study, 15 physical impacts on railway tracks resulting from climate hazards were identified and are listed in detail in Table 4. The identified impacts were classified into three primary categories: structural, geotechnical, and hydrological engineering. Structural impacts refer to damage to the structural components of the track, such as rails and sleepers. Geotechnical impacts involve damage to the granular materials such as ballast and embankments. Hydrological impacts encompass failures in water management systems associated with the track, such as inadequate drainage capacity, unexpected flooding, and drainage malfunctions. As observed in Table 4, in total, six structural (designated as S1 to S6), six geotechnical (designated as G1 to G6), and three hydrological impacts (designated as H1 to H3) were identified. This classification can assist managers in effectively allocating expert resources for detailed future risk assessments.

Similar to climate hazards, the identified physical impacts were ranked based on the level of attention they received in the literature. The 15 identified physical impacts were mentioned 126 times across the 71 collected studies. The ten most studied physical impacts are presented in

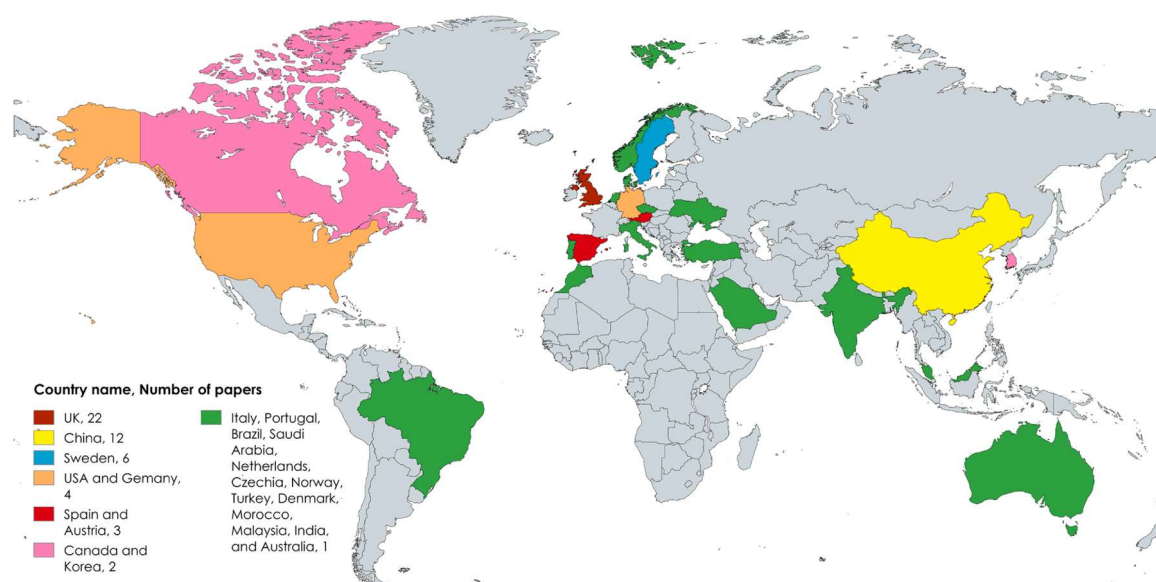


Fig. 5. Global distribution of the collected papers.

Fig. 8a. These include thermal stress and rail buckling, and flooded tracks. They are followed by landslides, erosion, scour, washout, track deformation, and so on.

Furthermore, as depicted in Fig. 8b, 25.8 %, 43.0 %, and 31.3 % of the total identified impacts are related to structural, geotechnical, and hydrological engineering fields, respectively.

4.2.2.2. Operational impacts. A comprehensive list of climate hazard impacts on the operation and maintenance of railway tracks has been identified, as presented in Table 5. As observed, 14 operational and maintenance (designated as O1 to O14) impacts are presented and briefly described based on related studies.

The 14 identified operational impacts were also sorted based on the number of times they were addressed in the reviewed papers. These impacts were mentioned a total of 101 times across the studies. Fig. 9 illustrates the frequency with which the top ten operational impacts of climate hazards on railway networks are mentioned in various studies.

Service disruptions and speed limitations (O1) are the most frequently discussed, appearing in 39 instances, underscoring their significant concern in the context of railway operations. Increased monitoring and maintenance (O14) follow with 13 mentions, points to the heightened need for proactive/reactive measures in response to climate impacts. The frequent mention of O1 and O14 can be attributed to the fact that many other physical/operational impacts can also lead to these two impacts. Other notable operational impacts are trees falling on tracks, avalanches blocking tracks, delays in maintenance activities, switches and crossing malfunctions, etc.

4.3. Hazard-impact relations

The relationships between the identified climate hazards and their induced impacts on railway infrastructure and operations are visually represented in Fig. 10. This matrix is built based on the data extracted from the reviewed articles. It allows for a comprehensive overview of how different climatic hazards affect both the physical and operational efficiency of the railway system. The intersections between the rows and columns are marked with yellow color, indicating where a particular climate hazard is linked to a specific impact.

The matrix in Fig. 10 also helps identify which climate hazards have the broadest range of impacts on railway systems and which impacts are influenced by the most climate hazards. Totals at the end of each row and column show the number of impacts each hazard influences and the

number of hazards affecting each impact, respectively. Based on this analysis, the top affecting climate hazards are storms (SH8) with 23 impacts, heavy rainfall (PH7) with 21 impacts, and heavy snowfall (PH8) with 19 impacts. Flooding (SH3) and coastal flooding/storm surges (SH4) follow with 18 and 17 impacts, respectively. On the other hand, the top impacts affected by the most climate hazards are increased monitoring and maintenance needs (O14) with 25 hazards, and track deformation (G2) and concrete degradation (S4) with 17 hazards each. Track instability (G4) and service disruptions/speed limitations (O1) follow with 14 hazards each. It is essential to note that the O14 risk is affected by all climate hazards, emphasizing the vital role of monitoring and maintenance activities in adapting to and mitigating climate-induced risks.

The provided matrix facilitates understanding the interplay between climate hazards and impacts. For instance, it shows how higher mean temperatures and heatwaves not only cause thermal stress and rail buckling but also lead to service disruptions and increased maintenance requirements. This holistic view underscores the multifaceted nature of climate risks, demonstrating that single hazards can have diverse impacts on railway systems and a specific impact can be triggered by various hazards. Hence, it aids in the development of reliable risk assessment for climate adaptation strategies.

4.4. Risk interconnection

Certain risks are interdependent, where the occurrence of one risk can trigger a cascade of subsequent risks (Gustafsson et al., 2023). For instance, thermal stress and rail buckling (S1) can lead to delays in maintenance (O13) and increased monitoring and maintenance needs (O14) (Palin et al., 2013). Similarly, landslides (G1) have cascading effects, potentially causing track deformations (G2), service disruptions and speed limitations (O1), and subsequently leading to increased monitoring and maintenance needs (O14). Therefore, it is crucial to consider the identified risks holistically, rather than examining them in isolation. In this regard a comprehensive list of interconnections between physical and operational climatic impacts on railway infrastructure is provided in Fig. 11. This matrix reveals the complex nature of climate-induced impacts on railways, helping risk managers understand how various climatic risks are interconnected and enabling more comprehensive risk identification during climate risk assessments.

Table 3
Primary and secondary identified climate hazards.

	Code	Hazard	Description	Study No.*
Primary hazards	PH1	Higher mean temperatures	An increase in the long-term average temperature of a region or the globe over a specific period, relative to the baseline average.	2, 3, 4, 11, 17, 18, 23, 27, 28, 31, 32, 33, 35, 37, 43, 44, 49, 50, 58, 64, 67, 69, 71
	PH2	Heatwaves	A prolonged period (e.g., two or more consecutive days) of high temperatures exceeding the historical average (e.g., by 5 °C).	1, 9, 16, 18, 29, 37, 50, 61, 62, 64
	PH3	Cold spells	A prolonged period (e.g., two or more consecutive days) of abnormally low temperatures relative to the historical average.	61
	PH4	Freeze-thaw cycles	Repeated cycles of thawing and freezing temperatures.	2, 18, 21, 35
	PH5	Changes in seasonal temperature pattern	Alterations in the typical temperature patterns expected during different seasons.	3, 49, 53, 58, 63
	PH6	Extreme temperature fluctuations	Rapid and significant changes in temperature within short periods.	14, 53
	PH7	Heavy rainfall	A high rate of rainfall within a specific region, exceeding a predefined threshold (e.g., >25 mm/day).	1, 2, 3, 4, 10, 13, 14, 15, 16, 17, 18, 20, 22, 25, 26, 30, 31, 33, 38, 41, 42, 44, 46, 47, 48, 49, 52, 55, 57, 58, 59, 63, 65, 67, 68, 70, 71
	PH8	Heavy snowfall	Large accumulations of snow over a specific period, exceeding a predefined threshold (e.g., >15 cm in 24 h).	13, 21, 30, 38, 49, 57
	PH9	Changes in seasonal precipitation pattern	Variations in the expected timing and amount of seasonal precipitation.	3, 49, 53
	PH10	Extreme winds	Unusually strong, sustained, or frequent winds that exceed predefined threshold speeds (e.g., greater than 90 km/h).	4, 5, 12, 13, 17, 24, 28, 30, 31, 34, 38, 40, 45, 57, 67
Secondary hazards	PH11	Higher sea level	Long-term rise in the average level of the world's oceans.	1, 9, 18, 28, 31, 44, 51, 58, 60, 66, 71
	PH12	Higher humidity	Increased moisture content in the air.	4, 35, 65
	PH13	Lower humidity	Decreased moisture content in the air.	18, 35, 56
	SH1	Frost degradation	A decrease in ice layer thickness in frozen ground due to the thawing.	28
	SH2	Frost heave	The upward movement of the ground surface caused by the formation and expansion of ice within the soil.	21
	SH3	Flooding	Floods are the overflow of water beyond the normal confines of rivers or streams (fluvial), or the accumulation of water in areas not typically submerged (pluvial). They are often caused by excessive rainfall, snowmelt, or excessive surface runoff.	1, 7, 9, 18, 22, 24, 25, 26, 28, 31, 36, 39, 46, 47, 48, 49, 52, 54, 58, 59
	SH4	Coastal flooding and/or storm surges	Flooding in coastal areas due to sea-level rise and/or strong winds and atmospheric pressure changes during storm surges.	6, 9, 51, 60, 66
	SH5	Change in the magnitude of wet-dry cycles	Alterations in the magnitude of annual wetting and drying conditions.	3, 65
	SH6	Drought	An exceptional period of water shortages due to low rainfall, high temperature, wind, high evaporation, soil moisture depletion, and/or water management issues.	1, 2, 3, 9, 18, 33, 65
	SH7	Changes in groundwater levels	Elevated or decreased levels of water stored underground.	3, 15, 18, 25, 53, 54, 63
	SH8	Storms	Storms are severe atmospheric disturbances characterized by strong winds combined with other hazards such as heavy snowfall (snowstorms), thunder and lightning (thunderstorms), intense rainfall (rainstorms), blowing sand and dust (sandstorms), violently rotating tornadoes, and massive cyclones (hurricanes, typhoons).	1, 4, 5, 8, 17, 18, 19, 30, 34, 38, 55
	SH9	Fog	Thick cloud of water droplets at ground level reducing visibility.	16, 30, 38
	SH10	Hail	Precipitation of ice pellets from severe thunderstorms.	5
	SH11	Icing events	Accumulation of ice on surfaces when rain falls on freezing surfaces or when meltwater from snow re-freezes during a freeze-thaw cycle.	4

* Note: The reference code and details information of references are given in Table A1.

4.5. Impacts of climate change on climate risks

This study identified climate risks that, according to the reviewed papers, are affected by climate change. Understanding the impacts of climate change on climate risks in railway infrastructure is critical for effective adaptation planning and ensuring the long-term functionality of transport systems (Kasraei et al., 2024; Palin et al., 2021). The literature reflects a range of approaches to address climate change impacts on the climate-related risk levels. These approaches can be categorized into four main groups: (1) descriptive link to future climate conditions, (2) qualitative link to climate risks, (3) simulated testing for future conditions, and (4) integrating climate change projections into risk assessments. Table 6 provides an overview of these approaches with respect to the collected papers.

Studies in the first category focus on assessing current climate risk levels to railway infrastructure, often through the analysis of historical data. For instance, research by Nezval et al. (2023) on storm-related

incidents in the Czech rail network, Tang et al. (2023) on urban rail transit risks under rainstorm conditions, Liu et al. (2018) on rainfall-induced failures in the Chinese railway system, and Ferranti et al. (2016) on heat-related failures in Southeast England's railway network fall into this category. Additional studies in this category are listed in Table 6. Most of the reviewed papers (48 out of 71) fall into this category. These studies are valuable for understanding the present state of climate risks; however, they establish only a descriptive or limited connection to future climate conditions. Indeed, they often mention how climate change could alter the frequency and intensity of climate hazards, and do not fully address how these changes might affect future risk levels.

The second group includes studies that use detailed climate models to project future climate conditions but do not integrate these projections directly into risk assessment. For example, Torvanger et al. (2024) employed CMIP6 climate models to project future weather conditions in Norway and estimate future risks to railways from climate

hazards like flooding and heat stress. Hänsel et al. (2022) utilized a regional climate model (e.g., EURO—CORDEX) under various RCPs to evaluate future temperature and precipitation trends and their impacts on transport infrastructure. Such an approach was also employed to discuss the impacts of future climate on rainfall-induced landslides in Europe (Schlögl & Matulla, 2018), extreme weather events affecting railway infrastructure in Austria (Kellermann et al., 2016a), and soil moisture variability on clay slopes in the UK (Clarke & Smethurst, 2010).

Simulated testing provides empirical data through controlled experiments that simulate future climate conditions. For instance, Kae-wunruen and Tang (2019) conducted experimental research to analyze the effects of flooding on stiffness and damping of railway ballast. You et al. (2018) investigated the impact of strong wind gusts on the dynamic stability of railway vehicles using wind tunnel experiments. Such studies offer useful empirical data for future adaptation planning. However, the applicability of the findings to real-world conditions is limited, as studies are often conducted in controlled settings. Additionally, these experiments require significant resources for setup and maintenance, and they typically focus on isolated variables rather than complex systems.

The most effective method for future-oriented risk management involves integrating climate change projections directly into risk assessments. For instance, Wang et al. (2024) utilized CMIP6 simulations to project global exposure of rail and road infrastructures to record-breaking climate extremes under different SSP scenarios. Kasraei

et al. (2024) applied the Cox Proportional Hazard Model to link meteorological variables with the reliability of railway assets. They conducted a reliability analysis of these assets to assess how asset failure rates may shift under various RCP scenarios. Liu et al. (2023) adopted a probabilistic approach to assess resilience in Great Britain's railway network, linking high-temperature projections under RCP8.5 with the risk of track buckling. Liu et al. (2021) used a random forest machine-learning model with CMIP5 data under RCP4.5 and RCP8.5 scenarios to evaluate the susceptibility of Chinese railway infrastructure to extreme precipitation. Villalba Sanchis et al. (2020) employed Monte Carlo simulations to estimate rail buckling events in Spain under various RCP scenarios. Additional contributions in this direction are presented in Table 6. In summary, this approach seeks to quantify the potential effects of climate change on the future level of risks under different climate scenarios. Therefore, such studies offer actionable insights for helping decision-makers to accurately design and plan for long-term adaptation strategies.

4.6. Highlighting gaps and guiding future research

This section identifies key gaps in the current body of literature on climate change risks on railway infrastructure. Addressing these gaps will enable future research to advance the understanding of climate change risks and support the development of effective adaptation strategies.

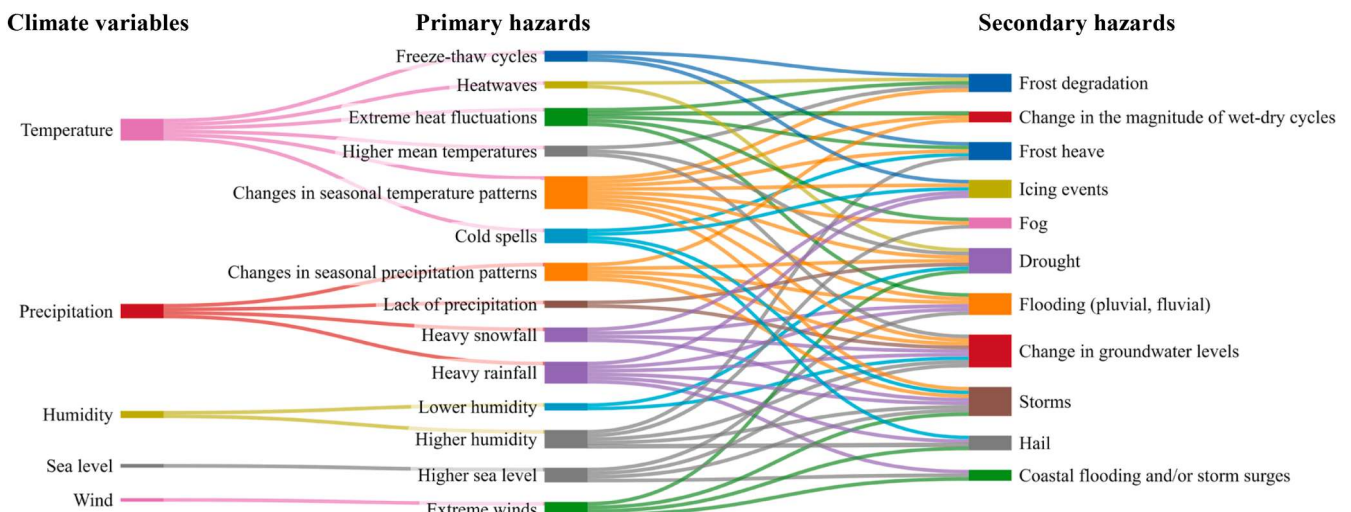


Fig. 6. The relations between climate variables, primary climate hazards, and secondary climate hazards.

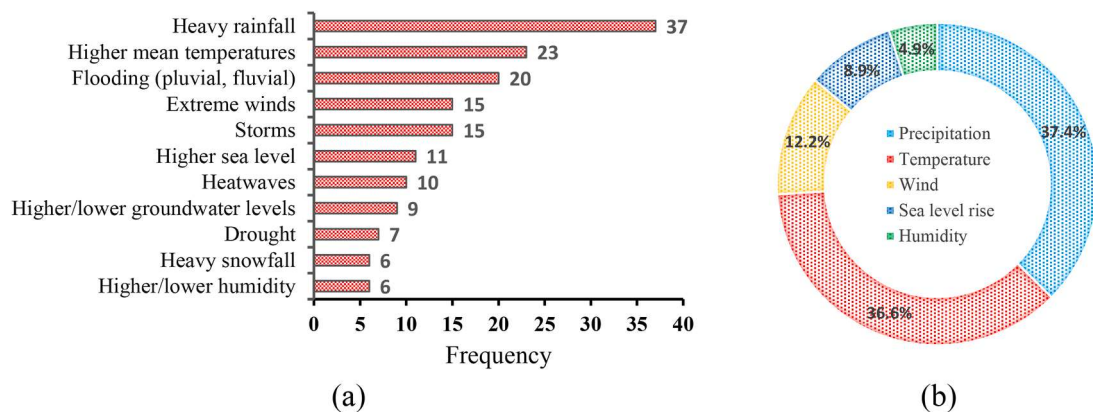


Fig. 7. (a) Top ten climate hazards based on their occurrence in the reviewed literature and (b) the contribution of climate variables to hazards.

Table 4
List of identified physical impacts on railway tracks.

Field	Code	Impacts	Description	Study No.*
Structural	S1	Thermal stress and rail buckling	Thermal stress occurs when temperature fluctuations cause rails to expand and contract, inducing stress within the rail material. Excessive heat can lead to rail buckling, where the track deforms or bends, posing significant safety risks and operational disruptions.	1, 2, 4, 9, 11, 16, 17, 18, 23, 27, 28, 29, 31, 32, 33, 37, 49, 50, 61, 62, 64, 67, 69
	S2	Long-term deformations in sleepers	Concrete sleepers experience long-term deformations called creep, where material slowly deforms under sustained load, and shrinkage, a short-term deformation that occurs due to drying. These deformations can cause track misalignment and require frequent maintenance to ensure track stability.	35, 56
	S3	Change in prestressing force in sleepers	Prestressed concrete sleepers use pre-applied tension to enhance load-bearing capacity. Variations in temperature and humidity can cause differential expansion and contraction, altering the prestressing force. This leads to a reduced ability to maintain track alignment and support loads effectively, impacting overall track performance.	35
	S4	Concrete degradation	Concrete degradation, involving physical wear, chemical reactions (like alkali-silica reaction, carbonation), exposure to cyclic loads, corrosion of steel reinforcement, and exposure to chlorides/sulfates, leads to cracking, spalling, fatigue, and reduced structural integrity over time, compromising the safety and functionality of sleepers.	14, 22, 35, 43
	S5	Steel degradation	Steel components such as rails, fasteners, and wires embedded in sleepers are susceptible to corrosion from moisture, chloride ions found in de-icing salts, and carbonation of concrete. Corrosion gradually undermines the steel's strength and threatens the structural integrity of the track.	18, 43, 44
	S6	Higher dynamic loads	Changes in track stiffness, caused by temperature fluctuations and varying moisture levels, can lead to uneven track support. This results in higher dynamic loads as trains pass over these sections, increasing stress on track components and accelerating wear and fatigue, thereby reducing overall track performance and safety.	36
Geotechnical	G1	Landslides	Landslides can occur along railway embankments or cuttings due to heavy rainfall, snowmelt, or geological instability. They can lead to sudden ground movements that disrupt the track alignment, cause embankment failures, and potentially derail trains, posing significant safety risks and requiring extensive repair efforts.	1, 3, 5, 8, 16, 24, 26, 31, 33, 41, 42, 46, 55, 58, 65, 68, 70
	G2	Track deformation	Track deformation encompasses various physical changes in track, such as settlement (elastic, consolidation, and creep), heaving (upward movement), or lateral displacement. Factors like freeze-thaw cycles, heavy rainfall, cumulative cyclic damages, and fluctuating moisture or groundwater levels contribute to these deformations. They can lead to uneven track surfaces, compromising alignment and safety.	2, 3, 14, 15, 18, 20, 21, 22, 25, 28, 44, 53, 54, 57
	G3	Changes in track stiffness	Track stiffness affects the track's ability to distribute loads and maintain alignment. Changes in stiffness can occur due to factors like icing/melting water in the soil, wetting/drying cycles of soil, and infiltration of fine particles in the ballast. These changes can lead to uneven settlement, increased stress on track components, and reduced operational safety.	2, 15, 20, 21, 28, 36, 54
	G4	Track instability	Track instability, particularly due to reduced bearing capacity, signifies a decrease in the ability of railway tracks to withstand dynamic train loads effectively. This condition results in uneven settlement, alignment problems, and potential track failures, which pose significant operational and safety risks.	2, 3, 15, 18, 26, 36, 52, 57, 65, 67, 70
	G5	Clay problems	Clay soils in tracks can experience reduced permeability, desiccation, desiccation cracking, and swell-shrink behavior. These issues arise from the soil's sensitivity to moisture variations, including lack of precipitation, seasonal changes, and prolonged drought. Such conditions can lead to impermeability, instability, and settlement problems in the track structure.	1, 2, 3, 53, 65
	G6	Seepage	Seepage refers to the infiltration or steady-state flow of water in the track structure, leading to settlement, drainage, and erosion issues.	8
Hydrological	H1	Erosion, scour, and washout	Long-term erosion and scour, as well as short-term washout of granular track materials, result in the loss of the track supports. These phenomena are caused by gradual weathering and prolonged water flow, as well as sudden and intense water flow during heavy rain, flooding, or storms. These phenomena can lead to track bed degradation, settlement, and potentially hazardous conditions for train operations.	1, 10, 18, 22, 25, 33, 39, 44, 46, 47, 48, 49, 51, 52, 58, 60
	H2	Coastal erosion	Coastal erosion threatens railway tracks located near shorelines, leading to the gradual loss of land and infrastructure. Wave action, tidal forces, and storm surges erode track foundations, compromising the stability and performance of the track.	31, 44, 51, 60, 66, 71
	H3	Flooded/inundated track	Flooded or inundated tracks occur when water levels rise above track surfaces due to heavy rainfall, flooding, or storm surges. This inundation can disrupt train operations, damage track components, and necessitate extensive cleanup and repair efforts to restore functionality and safety.	5, 6, 7, 8, 9, 16, 17, 26, 31, 33, 39, 46, 47, 48, 52, 55, 58, 59, 60, 66

* Note: The reference code and details information of references are given in Table A1.

4.6.1. Underexplored geographic regions

The country distribution of the reviewed studies reveals a concentration of research in specific regions, with the majority of contributions originating from European countries, North America, and China. In contrast, nationwide studies are notably lacking in many parts of Asia, Africa, and other developing regions. Given that climate hazards and their associated impacts can vary significantly across regions due to

local climatic conditions, geographic features, and infrastructure vulnerabilities, this geographic imbalance is concerning (IPCC, 2022; Wang et al., 2020). For instance, sandstorms and sand/dust deposition pose critical challenges to railway tracks and operations in desert regions, such as those in the Middle East (Esmaeili et al., 2019). However, this review identified only one study explicitly addressing these impacts (Almujibah et al., 2022). Hence, the geographic imbalance in the

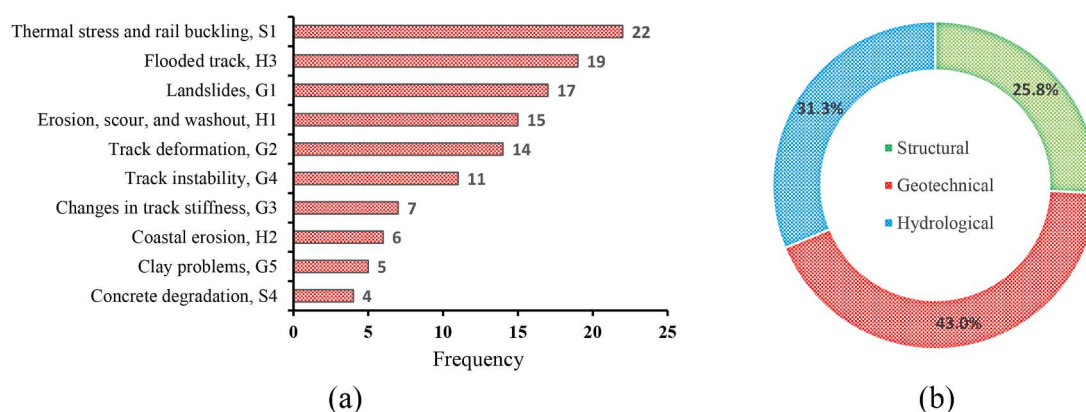


Fig. 8. (a) Top ten physical impacts based on their occurrence in the reviewed literature and (b) distribution of the identified physical impacts based on their related fields.

literature underscores the need for more region-specific, nationwide climate risk studies that account for unique local challenges.

4.6.2. Underexplored climate risks in railway infrastructure

The analysis of the literature attention conducted in Section 4.2 reveals specific climate risks that have received insufficient study. For example, while the risks of thermal stress and rail buckling have been extensively evaluated (see Table 4), the impact of extreme cold conditions on rail breakage (another temperature-related risk) due to climate change has not been studied adequately. This issue is particularly critical in regions with severe winters (Skarova et al., 2022). Similarly, snow and ice buildup on tracks is a prevalent risk in cold climates (Lotfi & Virk, 2023), accounting for 82 % of climate-related failures in Sweden (Soleimani-Chamkhorami et al., 2024). Despite its significance, this risk has not been thoroughly examined in the context of climate change. Furthermore, there is a notable lack of effective adaptation strategies, such as predictive models and early warning systems to mitigate this risk.

Another underexplored risk is slippery tracks caused by wet or icy conditions or leaf buildup during autumn and winter in European countries (Thaduri et al., 2021). The operational impacts of this risk and its potential amplification due to climate change have not been studied in detail (Palin et al., 2013). Based on the analysis of literature attention conducted in this study, other risks requiring more attention include changes in prestressing forces in sleepers, water seepage into railway tracks, and reduced visibility. These underexplored risks necessitate targeted studies to better understand their implications under changing climate conditions and to develop effective mitigation and adaptation strategies (Palin et al., 2021; Wang et al., 2020).

4.6.3. Limited use of advanced climate scenarios

As noted above, the transition from assessing current risks to predicting future climate impacts remains a significant challenge in climate risk research. While studies using climate projections and experimental simulations provide some foresight, quantitative methodologies that integrate climate projections into risk modeling are essential for actionable and long-term adaptation strategies. Such approaches offer a clearer understanding of future risks, enabling more informed decision-making. This review revealed the challenge of incorporating dynamic climate projections into climate risk analysis. Of the 71 reviewed papers, only 16 attempted to integrate climate projections into risk modeling (see Table 6), and five utilized the latest Shared Socioeconomic Pathways (SSPs). The remaining studies relied on other scenarios, such as Representative Concentration Pathways (RCPs). The adoption of SSPs is still limited. Future research should prioritize the development of integrative, quantitative risk models that incorporate the latest climate scenarios.

4.6.4. Limited application of emerging technologies

Emerging technologies like Artificial Intelligence (AI) and Machine Learning (ML) offer promising tools for advancing climate risk management in railway infrastructure (Tang et al., 2022). However, this review reveals that only a limited number of studies have applied these technologies. These include the use of ML algorithms to predict weather-induced delays (Chen et al., 2021), analyze rainfall-induced impacts under global warming scenarios (Liu et al., 2018, 2021), and estimate rail temperatures based on weather variables and solar radiation (Hong et al., 2021).

Despite the demonstrated benefits of these technologies (Argyroudis et al., 2021; Tang et al., 2022), this review highlights their application in climate risk management remains in its early stages. Future studies can focus on developing and applying advanced AI and ML frameworks to improve predictive accuracy and optimize adaptation strategies.

4.7. Comparison with the existing review papers

Due to the embryonic nature of this research field, the number of studies is limited, and comprehensive literature reviews are also rare. However, during our survey, we identified four relevant review papers. Each of these review papers has contributed uniquely to the understanding of climate resilience in railway infrastructure. Table 7 presents an overview of this study and existing review papers, highlighting their differences and contributions to the literature.

5. Applications and limitations of the study

As discussed in previous sections, the findings of this study can contribute to improving climate risk management for conventional railway infrastructure in several ways. Furthermore, although this study focused on identifying a broad range of climate hazards and impacts on railway tracks and operations on a global scale, its results can be utilized for preliminary risk identification in a specific region by following these steps:

- Step 1:** Choose a specific region, considering its unique climatic and geographical features influencing hazard relevance and severity.
- Step 2:** Use regional climate data and projections to analyze historical and future climate trends, including changes in temperature, precipitation, and wind patterns.
- Step 3:** Refer to Fig. 6 to identify primary and secondary climate hazards pertinent to the region.
- Step 4:** Use Figs. 10 and 11 to connect climate hazards with potential impacts. These figures present hazard-impact relationships and interconnections of impacts, aiding in identifying possible risks.

Table 5

List of identified operational impacts on railway tracks.

Code	Impact	Description	Study No.*
O1	Service disruptions and speed limitations	Extreme weather conditions like heavy precipitation, heatwaves, high winds, and storms disrupt scheduled services, causing delays and cancellations. Trains may also need to operate at reduced speeds during adverse weather, impacting travel times, operational efficiency, passenger convenience, and supply chain reliability.	1, 2, 4, 7, 8, 13, 18, 19, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 37, 38, 41, 42, 45, 46, 47, 48, 49, 50, 51, 55, 57, 58, 59, 61, 63, 64, 69, 71
O2	Reduced visibility	Weather events such as fog, heavy rain, or snow significantly reduce visibility for train operators, increasing the risk of collisions and derailments, necessitating additional safety protocols.	1, 5, 16, 19
O3	Snow and ice buildup on track	Accumulation of snow and ice on tracks, switches, and crossings can obstruct train movement, requiring extensive clearing efforts and causing delays and operational disruptions.	1, 4, 49, 57
O4	Avalanches blocking the track	Avalanches occur when a large mass of snow, rock, or soil rapidly descends from slopes/cuts, often triggered by heavy precipitation. They can bury railway tracks under debris, causing immediate blockages.	1, 31, 58, 63, 68
O5	Wildfires	Fires in forested areas near railway lines, often intensified by dry and hot conditions, can damage infrastructure, create hazardous air quality, and lead to service suspensions for safety reasons.	1, 18, 33
O6	Preventing access to the station/track	Flooding and ponding from heavy rains or poor drainage systems can make it difficult for passengers and maintenance crews to access stations and tracks, potentially causing service suspensions.	8, 17, 18
O7	Safety issues for workers	Extreme weather conditions, such as high temperatures causing heat stress or severe storms inducing panic, can pose health and safety risks to workers, affecting their ability to perform duties efficiently and safely.	8, 18, 50, 61
O8	Trees fall on the track	Strong winds, storms, or unstable soil conditions can cause trees to fall onto tracks, requiring immediate removal to restore service and potentially causing damage to rails and overhead lines.	5, 12, 16, 18, 31, 45, 57, 67
O9	Trees extending into clearance profile	Overgrown vegetation can encroach on the clearance profile of railway tracks, obstructing trains and necessitating regular trimming and vegetation management to maintain safe operations.	5
O10	Foreign objects on the track	Flooding and strong winds can deposit debris such as branches, rocks, and sand onto tracks, creating hazardous conditions that need to be cleared promptly to ensure safe train operations.	8, 17, 19, 57
O11	Slippery track and train brake problems	Slippery tracks due to the wet or icy conditions or leaves on rails can reduce traction and braking effectiveness, increasing the risk of accidents and requiring enhanced maintenance and safety protocols to address these issues.	4, 57, 61
O12	Switches and crossing malfunction	During adverse weather conditions like high temperatures, snow, and ice can cause failures in switches and crossings, leading to operational disruptions and requiring immediate repair to restore functionality and ensure safety.	4, 5, 18, 49, 57
O13	Delay in maintenance	Adverse weather conditions can hinder maintenance, reducing the time available for scheduled activities. For example, hot weather can increase the risk of rail buckling, requiring some maintenance tasks to be postponed.	16, 29, 31, 50, 61
O14	Increased monitoring and maintenance needs	Climate change-induced weather variability necessitates more frequent and detailed inspections and maintenance activities to ensure infrastructure integrity and safety, increasing operational costs and resource allocation.	1, 2, 3, 4, 21, 23, 26, 49, 51, 63, 67, 69, 70

* Note: The reference code and details information of references are given in Table A1.

Step 5: Use a framework such as the one in Fig. 2 to carry out detailed risk assessments. This involves identifying additional potential risks and thoroughly analyzing and evaluating the identified risks.

It should be noted that the findings of this literature review are also subject to some limitations, which are outlined as follows:

- The identified hazards, impacts, and their interactions are incomplete. As climate science progresses and new data emerges, continuous updates are necessary to ensure relevance and accuracy.
- The hazard-impact relationships and impact interconnections presented in this study are based on a systematic literature review. Further empirical surveys and field studies are needed to enhance the accuracy of these relationships and complex interactions.
- The risk prioritizations do not offer conclusive assessments of the severity and likelihood of the identified risks since they may vary based on local challenges. The criticality of each climate risk varies by region, necessitating extensive localized research to determine the most significant climate risks for specific areas and assets.

- The paper focused on the components of conventional railway tracks. However, there is a need to explore other critical assets, including structures, rolling stock, power supplies, and signaling systems.

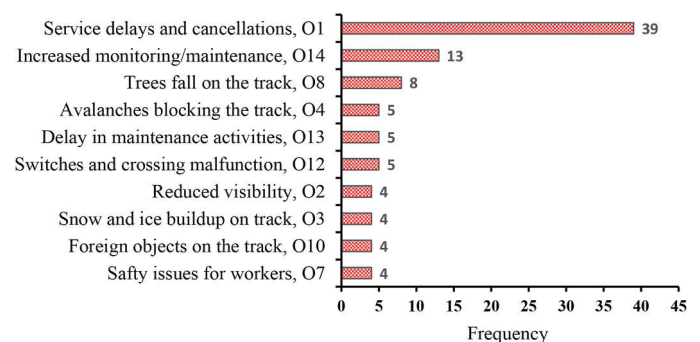


Fig. 9. Top ten operational impacts based on their occurrence in the reviewed literature.

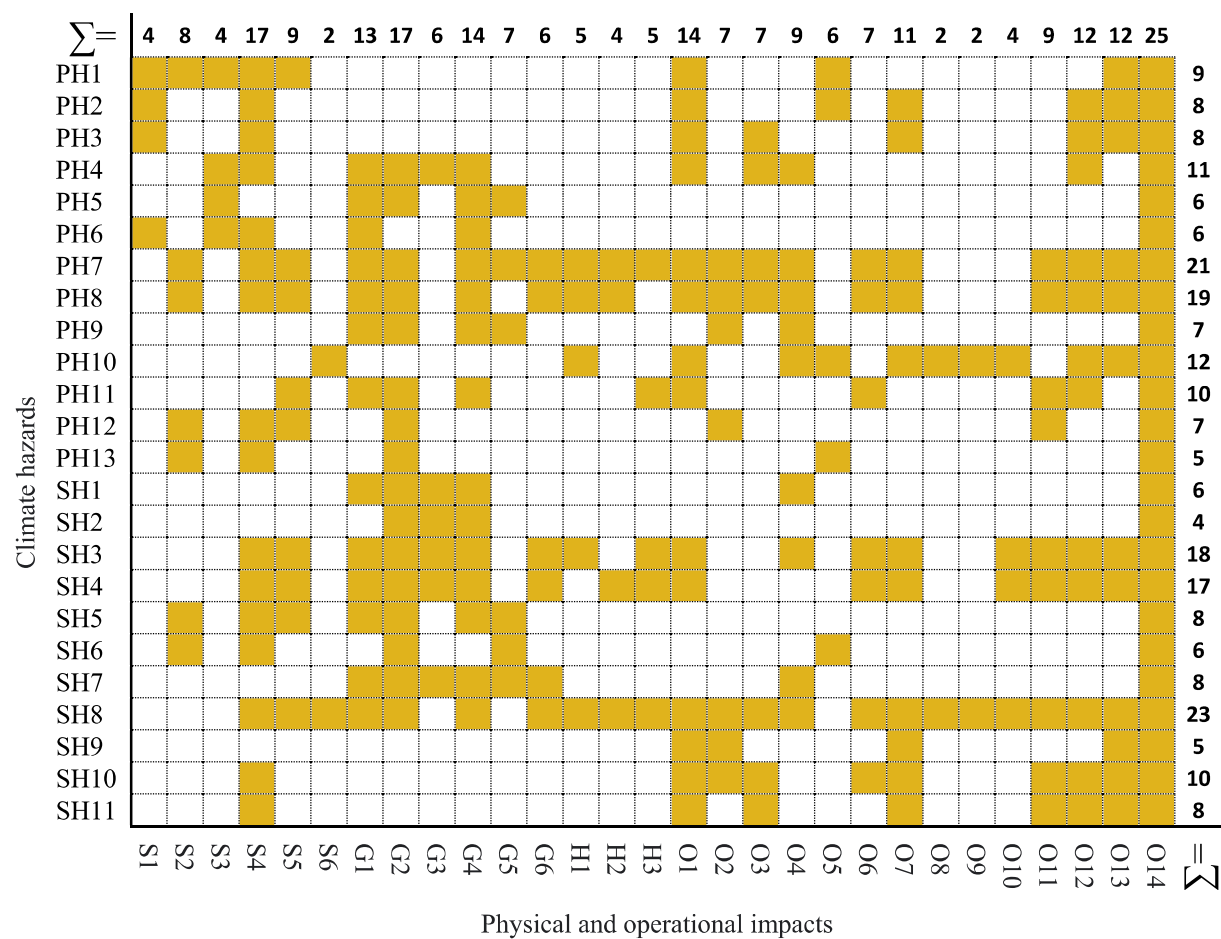


Fig. 10. The relationships between the identified climate hazards and their induced impacts on railway.

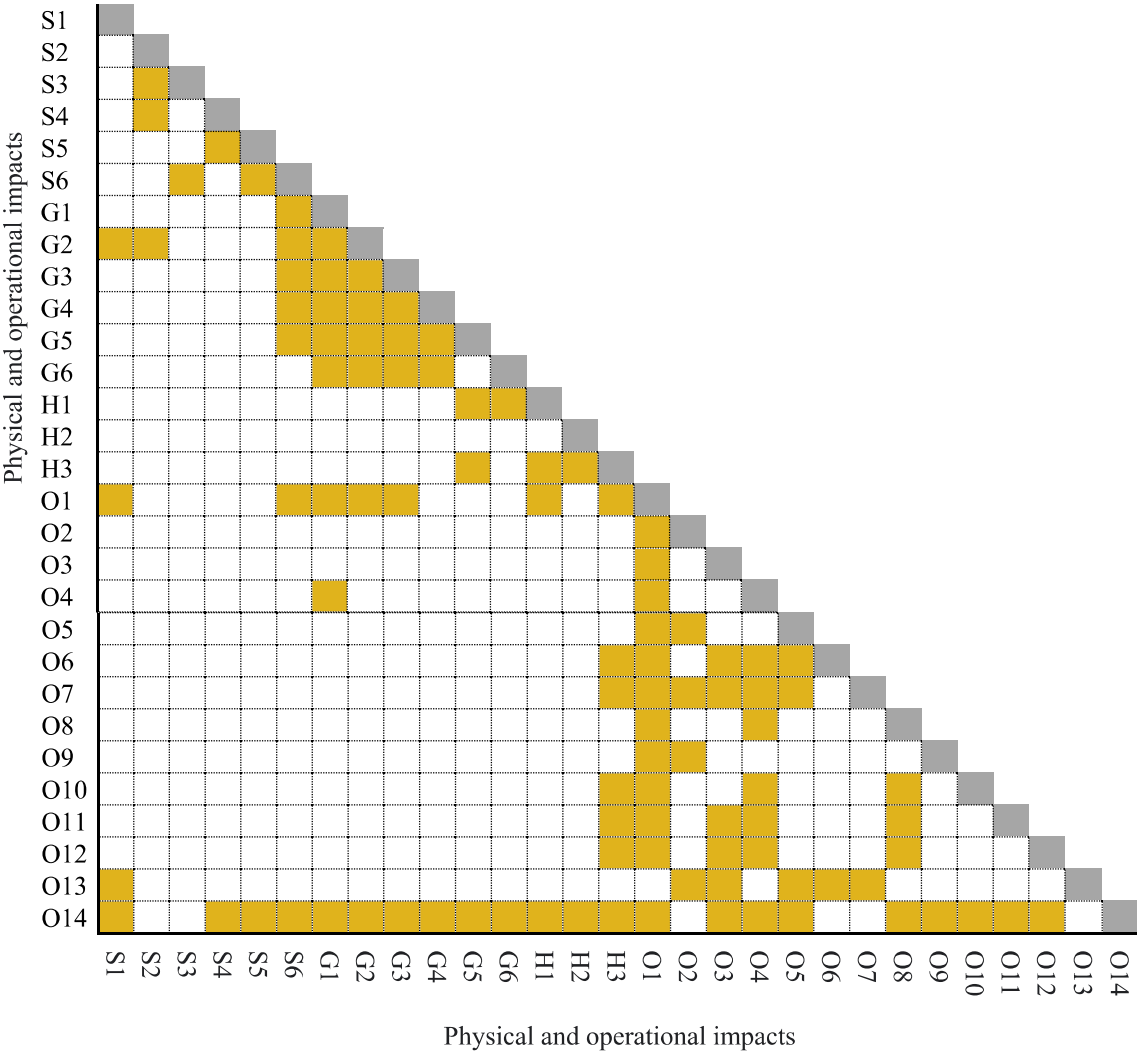


Fig. 11. The interconnections between the identified climate impacts on railways.

6. Conclusion

This study focused on reviewing the risks associated with climate change to railway infrastructure, operation, and maintenance. To this end, a systematic literature review was conducted, resulting in the collection of 71 peer-reviewed and relevant articles. The collected dataset was then subjected to detailed content analysis to achieve the research objectives. The main findings are as follows:

- Five climate variables were identified to be predominant for climate hazards. This includes precipitation, temperature, wind, sea level, and humidity.
- 24 climate hazards were identified, categorized into 13 primary and 11 secondary hazards. Primary hazards are direct outcomes of climate anomalies, such as heavy rainfall. Secondary hazards arise from cascading effects (e.g., flooding from heavy rainfall) or interactions between primary hazards (e.g., rainstorms combining extreme wind and rain). This classification underscores the multifaceted and hierarchical nature of climate hazards.
- 29 climate-related impacts were identified and categorized into 15 physical and 14 operational impacts. Physical impacts directly damage railway infrastructure and were classified into structural (e.g., rail buckling), geotechnical (e.g., landslides), and hydrological (e.g., flooded track) impacts. Operational impacts include service disruptions, delays, maintenance issues, and safety risks arising directly

from climate hazards or as consequences of the physical impacts. These actionable categorizations assist railway managers and decision-makers in effectively allocating expert resources to conduct detailed risk assessments.

- The identified climate hazards and impacts were prioritized based on their occurrence in the literature to highlight which hazards/impacts are frequently studied and which are underexplored. It was revealed that heavy rainfall, higher mean temperatures, flooding, extreme winds, and storms are among the most frequently studied climate hazards. In addition, thermal stress and rail buckling, flooded tracks, landslides, service disruption, and increased maintenance demands were identified as significant impacts.
- An informative matrix was created to correlate climate hazards with their impacts. It demonstrated that storms, heavy precipitation, floods, seasonal temperature changes, and extreme winds are the most significant climate hazards due to their wide-ranging impacts. The matrix also showed that increased monitoring, maintenance needs, track deformation, concrete degradation, and service disruptions are common impacts triggered by various climate hazards. These insights facilitate further multi-hazard or multi-impact risk assessments and support prioritization for adaptation strategies.
- The complex interplay of risks and their cascading effects were also illustrated, such as how rail buckling can lead to increased maintenance needs, demonstrating the importance of integrated strategies to address cascading and compound climate risks.

Table 6

Overview of approaches for considering climate change impacts in climate risks assessment of railways.

Approach	Description	Key insights	Challenges/limitations	Study No.*
Descriptive link to future climate conditions	Analyzes existing risks using historical data and current conditions, often establishing a descriptive link to future climate conditions.	✓ Offers insights into current risk levels. ✓ Provides methodologies for assessing climate risks. ✓ Informs immediate adaptation and mitigation strategies.	• Does not establish a strong link to climate projections. • Limited in guiding for long-term adaptation planning. • Challenges in managing uncertainties in risk analysis.	Others
Qualitative link to the climate risks	Uses climate models to project future climate hazards, generally providing qualitative associations with climate risks.	✓ Provides detailed projections of future climate conditions. ✓ Offers insights into potential changes in hazards and/or exposure based on projected climate conditions.	• Lacks direct integration of climate projections into the risk analysis, limiting actionable adaptation strategies. • Limited by the underlying assumptions present in the climate projections that were used. • Challenges in managing uncertainties in climate projections.	1, 16, 41, 49, 65
Simulated testing for future conditions	Conducts experimental studies in controlled environments to simulate and observe infrastructure performance under specific climate conditions.	✓ Provides empirical data on asset performance under specific projected climate conditions.	• Limited applicability to real-world conditions due to controlled settings. • High resource requirements for experimental setups. • Often focused on isolated variables.	36, 40
Integrating climate change projections into risk assessments	Integrates climate projections with risk analysis to evaluate the impacts of climate change on risk levels.	✓ Assesses future climate risk levels based on specific climate scenarios. ✓ Provides robust, actionable insights for future adaptation strategies. ✓ Supports precise planning for climate-resilient infrastructure.	• Requires high-quality data and complex modeling. • Challenges in managing uncertainties in climate projections and risk analysis. • Demands interdisciplinary expertise. • Few studies address the latest climate scenarios (e.g., SSPs).	2, 3, 4, 9, 11, 23, 26, 32, 37, 39, 51, 61, 64, 66, 69, 70

* Note: The reference code and details information of references are given in Table A1.

Table 7

Comparison of the present study and other review papers.

Study	Paper collection	Scope	Main Objective	Key Contributions
Wang et al. (2020)	Systematic	Global road and rail transport	Reveal the status quo and potential challenges based on research themes	✓ Categories papers into different research directions such as climate risk assessment, asset management, planning, and adaptation ✓ Provides insights on understanding climate adaptation, risk analysis, and planning ✓ Highlights potential gaps, particularly in adaptation strategies
Palin et al. (2021)	Non-systematic	Global railway infrastructure	Address challenges in climate change risk assessment and adaptation	✓ Emphasizes modification in traditional risk assessment methods ✓ Points out the main challenges such as managing uncertainties, decoding weather-impact relationships, and understanding the adaptation requirements ✓ Highlights a lack of policy and knowledge in adaptation strategies
Lotfi and Virk (2023)	Non-systematic	Railway infrastructure and rolling stock in cold regions	Identify the challenges and solutions for operation	✓ Points out gaps in winter weather research ✓ Calls for optimal and cost-effective ice mitigation methods to minimize icing effects
Kostianaia and Kostianoy (2023)	Non-systematic	Railway infrastructure in high-latitude regions	Review adaptation strategies	✓ Provides adaptation considerations in Canada, China, and Sweden ✓ Provides recommendations for adaptation approaches
This Study	Systematic	Global railway infrastructure	Review climate hazards and their posed impacts	✓ Provides a comprehensive categorized list of climate hazards and impacts ✓ Maps hazard-impact relationships and highlights risks in interconnections and cascading effects ✓ Provides an organized archive of studies linked to specific hazards and impacts ✓ Supports preliminary regional risk identification ✓ Points out potential gaps and guides future research

- The identified climate hazards and impacts are on a global scale. However, the findings can be utilized for preliminary risk identification in a specific region.
- Four distinct approaches to addressing the impacts of climate change on climate risks were identified and discussed: (1) descriptive links to future climate conditions, (2) qualitative links to climate risks, (3) simulated testing under future conditions, and (4) integration of climate change projections into risk assessments.
- Four critical gaps in the current body of literature were also identified to guide future research. These include underexplored

geographic regions and climate risks, insufficient use of advanced climate projections under the latest climate scenarios like SSPs in risk assessment, and limited application of emerging technologies like AI and ML.

- In complementing the existing literature, this study presents a comprehensive systematic review of climate hazards affecting railway infrastructure. It offers a structured classification of hazards and their associated impacts, maps interconnections and cascading effects, and provides an organized archive of relevant studies to support regional risk identification and guide future research.

Although these findings provide valuable insight into climate risk management and resource allocation for conventional railway infrastructure, some limitations remain. The paper relies on the available literature, which means that emerging or less-documented hazards might not be fully represented. Furthermore, the study focused on conventional railway track components but should be expanded to include other railway assets. Future research and continuous updating should address these limitations.

AI ethics statement

The authors employed ChatGPT4o to enhance the language and readability of this manuscript. After using this tool, the authors reviewed and edited the content and took full responsibility for the final version.

CRedit authorship contribution statement

Ehsan Haghighi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ahmad Kasraei:** Writing – review & editing, Writing – original draft, Supervision, Methodology,

Investigation. **Stephen Famurewa:** Writing – review & editing, Supervision. **Gustav Strandberg:** Writing – review & editing, Supervision. **Gabriel Sas:** Writing – review & editing, Supervision. **A.H.S Garma-baki:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

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Appendix

Reference template of selected journal is not numeric based, therefore, to have better presentation of collected information, we have defined “Study No.” column and associated numbering label as given in [Table A1](#).

Table A1

. Summary of selected resources.

Authors	Aim of study	Climate hazard	Physical impact	Operational impact	Study No.
(Torvanger et al., 2024)	Presenting a ‘Preparedness framework’ for a comprehensive physical climate risk assessment.	PH2, PH7, PH11, SH3, SH6, SH8	S1, G1, G6, H1	O1, O2, O3, O4, O5, O14	1
(Wang et al., 2024)	Assess the exposure of global rail and road infrastructure to future record-breaking climate extremes under different development and emission scenarios.	PH1, PH4, PH7, SH6	S1, G2, G3, G4, G6	O1, O14	2
(Huang et al., 2024)	Investigate the impact of forecast climate change on pore-water pressure regimes within transport infrastructure earthworks in SE England.	PH1, PH5, PH7, PH9, SH5, SH6, SH7	G1, G2, G4, G6	O14	3
(Kasraei et al., 2024)	Assess how climate change impacts asset reliability and develop an effective methodology for infrastructure asset managers to adapt maintenance strategies.	PH1, PH7, PH10, PH12, SH8, SH11	S1	O1, O3, O11, O12, O14	4
(Nezval et al., 2023)	Investigate the impacts of storms on rail transport in Czechia and discuss mitigation measures.	PH10, SH8	G1, H3	O2, O8, O9, O12	5
(Martello et al., 2023)	Construct depth-damage curves for rail rapid transit facilities and assets to assess their fragility to saltwater flood exposure.	SH4	H3	–	6
(Wang et al., 2023)	Develop a decision-making model for optimal renovation sequence and investment timing for drainage systems in URT stations under the risk of extreme precipitation.	SH3	H3	O1	7
(Tang et al., 2023)	Explore the evolution of operational risks in URT systems under rainstorm disasters and propose optimized strategies to improve resilience and operational safety.	SH8	G1, G7, H3	O1, O6, O7, O10	8
(Sambo et al., 2023)	Develop an indicators-based approach for integrated assessment of multiple climate-related risks in the Metropolitan City of Venice and its lagoon.	PH2, PH11, SH3, SH6, SH10	S1, H3	–	9
(Liu et al., 2023)	Analyze the exposure of global transportation assets to changes in precipitation return periods under future warming scenarios.	PH7	H1, H3	–	10
(Li et al., 2023)	Assess the resilience of Great Britain’s railway system to high-temperature-related track buckling under RCP8.5 scenario.	PH1	S1	–	11
(Szymczak et al., 2022)	Develop a user-friendly GIS tool to estimate the hazard of tree fall along railway lines	PH10	–	O8	12
(Sun et al., 2022)	Develop a comprehensive risk assessment of meteorological hazards affecting Chinese high-speed railways.	PH7, PH8, PH10	–	O1	13
(Matias & Ferreira, 2022)	Investigate the long-term performance of concrete under extreme weather conditions.	PH6, PH7	S4, S6, G2	–	14
(Liu et al., 2022)	Assess the long-term impacts of extreme precipitation events on railway embankment.	PH7, SH7	G2, G3, G4	–	15
(Hänsel et al., 2022)	Provide climate services to support impact analyses and adaptation planning for the inland transportation system.	PH2, PH7, SH9	S1, G1, H3	O2, O8, O13	16
(Ferranti et al., 2022)	Evaluate the resilience of urban transportation infrastructure to extreme weather events	PH1, PH7, PH10, SH8	S1, H3	O6, O10	17

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Table A1 (continued)

Authors	Aim of study	Climate hazard	Physical impact	Operational impact	Study No.
(Attohi et al., 2022)	Identify the climate information services needed to support adaptation in the railway sector	PH1, PH2, PH4, PH7, PH11, PH13, SH3, SH6, SH7, SH8	S1, S5, G2, G4, H1	O1, O5, O6, O7, O8, O12	18
(Almujibah et al., 2022)	Develop effective methods for mitigating the impacts of sandstorms on the railway network in Saudi Arabia	SH8	–	O1, O2, O10	19
(Xie et al., 2021)	Evaluate the performance of unsaturated railway embankments under combined effects of rainfall and dynamic train loads	PH7	G2, G3	–	20
(Roghani, 2021)	Quantify the effect of freeze-thaw cycles and snow cover on track surface deformation and degradation of railway track geometry	PH4, PH8	G2, G3	O14	21
(Ridho & Kaewunruen, 2021)	Investigate the vulnerability of interspersed railway tracks exposed to flood and washaway conditions under moving train loads	PH7, SH3	S4, G2, H1	O1	22
(Mulholland & Feyen, 2021)	Quantify the increased operation and maintenance costs to railway infrastructures due to extreme heat corresponding to different global warming levels	PH1	S1	O1, O14	23
(Meesit & Andrews, 2021)	Identify and rank the critical sections of railway networks based on risk-based criticality to support robustness improvement strategies	PH10, SH3	G1	O1	24
(McKenna et al., 2021)	Derive fragility functions for granular embankments exposed to moisture ingress and scour to predict deformation and damage	PH7, SH3, SH7	G2, H1	–	25
(Liu et al., 2021)	Quantify the increasing costs to Chinese railway infrastructure by extreme precipitation under different global warming scenarios	PH7, SH3	G1, G4, H3	O1, O14	26
(Hong et al., 2021)	Develop a machine learning-based rail temperature prediction model to issue train-speed-limit warnings	PH1	S1	O1	27
(Garmabaki et al., 2021)	Qualitatively identify and assess the impact of climate change on railway infrastructure with associated risks and consequences	PH1, PH10, PH11, SH1, SH3	S1, G2, G3	O1	28
(Davies & Andrews, 2021)	Develop a Petri net model to assess the impact of summer heatwaves on railway track geometry maintenance	PH2	S1	O1, O13	29
(Chen et al., 2021)	Develop a model to predict weather-induced delays in high-speed rail and aviation systems in China	PH7, PH8, PH10, SH8, SH9	–	O1	30
(Greenham et al., 2020)	Identify and assess the impact of climate change on UK rail systems and provide a risk evaluation to support adaptation planning	PH1, PH7, PH10, PH11, SH3	S1, G1, H2, H3	O1, O4, O8, O13	31
(Villalba Sanchis et al., 2020)	Assess the impact of increasing temperatures on rail buckling in Spain's high-speed rail network and develop a methodology to predict buckling events	PH1	S1	O1	32
(Ortega et al., 2020)	Identify critical sections of the Spanish transport system due to climate scenarios	PH1, PH7, SH6	S1, G1, H1, H3	O1, O5	33
(Han et al., 2020)	Develop an integrated wind risk warning model for urban rail transport to improve safety during strong wind conditions	PH10, SH8	–	O1	34
(Li & Kaewunruen, 2019)	Investigate the effects of extreme climatic conditions on the performance of prestressed concrete sleepers	PH1, PH4, PH12, PH13	S2, S3, S4	–	35
(Kaewunruen & Tang, 2019)	Investigate the dynamic behavior of railway ballast under flooding conditions	SH3	S7, G3, G4	–	36
(Chinowsky et al., 2019)	Assess the impact of climate change on the operation of the US rail network and evaluate adaptation measures	PH1, PH2	S1	O1	37
(Chen & Wang, 2019)	Investigate the impact of severe weather events on the operational reliability of HSR and aviation in China	PH7, PH8, PH10, SH8, SH9	–	O1	38
(Bubeck et al., 2019)	Assess current and future flood risk to European railway infrastructure under different global warming scenarios	SH3	H1, H3	–	39
(You et al., 2018)	Investigate the dynamic behavior and safety of railway vehicles running on curved tracks during wind gusts	PH10	–	–	40
(Matthias & Christoph, 2018)	Assess the potential future exposure of European land transport infrastructure to rainfall-induced landslides throughout the 21st century	PH7	G1	O1	41
(Liu et al., 2018)	Proposed a risk analysis method to assess the risk to transportation networks from rainfall-induced multihazards	PH7	G1	O1	42
(Kaewunruen et al., 2018b)	Assess the influence of climate change on the performance and durability of concrete structures	PH1	S4, S5	–	43
(Kaewunruen et al., 2018a)	Investigate the georisks and potential consequences on track capacity and performance of railway systems under climate uncertainties	PH1, PH7, PH11	S5, G2, H1, H2	–	44
(Fu & Easton, 2018)	Develop a prototype data model to predict weather-related incidents on the rail network, focusing on wind-related delays	PH10	–	O1, O8	45
(Kalandari et al., 2017)	Quantify and map the probability of flooding at critical railway-stream intersection locations in Sweden	PH7, SH3	G1, H1, H3	O1	46
(Michielsen et al., 2016)	Predict and communicate flood risk for transport infrastructure using watershed characteristics	PH7, SH3	H1, H3	O1	47
(Kellermann et al., 2016b)	Apply the RAIL model to estimate flood damage and repair costs for railway infrastructure in Austria	PH7, SH3	H1, H3	O1	48
(Kellermann et al., 2016a)	Assess future implications of climate change on railway transportation in Austria	PH1, PH5, PH7, PH8, PH9, SH3	S1, H1	O1, O3, O12, O14	49
(Ferranti et al., 2016)	Examine heat-related failures in southeast England's railway network and implications for heat risk management	PH1, PH2	S1	O1, O7, O13	50
(Dawson et al., 2016)	Assess the impact of projected sea-level rise on the Dawlish to Teignmouth stretch of the London to Penzance railway line	PH11, SH4	H1, H2	O7, O14	51
(Sa'adin et al., 2016)	Assess the vulnerability of the Singapore-Malaysia high-speed rail system to heavy rainfall and flood events	PH7, SH3	G4, H1, H3	–	52

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Table A1 (continued)

Authors	Aim of study	Climate hazard	Physical impact	Operational impact	Study No.
(Smethurst et al., 2015)	Investigate the mechanical and hydrological impacts of tree removal on a clay fill railway embankment	PH5, PH6, PH9, SH7	G2, G6	–	53
(Jiang et al., 2015)	Evaluate the impact of water level rise on the performance of ballastless high-speed railway infrastructure	SH3, SH7	G2, G3	–	54
(Jaroszweski et al., 2015)	Analyze the impacts of the 28 June 2012 storms on UK road and rail transport	PH7, SH8	G1, H3	O1	55
(Bezgin, 2015)	Investigate the impact of climate effects on the shoulder width measurements of prestressed concrete high-speed railway sleepers of ballasted tracks	PH13	S2	–	56
(Ma et al., 2014)	Assess the impact of adverse weather on urban rail transit facilities using fault tree analysis and fuzzy synthetic evaluation	P7, PH8, PH10	G2, G4	O1, O3, O8, O10, O11, O12	57
(Doll et al., 2014)	Evaluate the impact of extreme weather events on rail and road networks in Southern Germany and Austria	PH1, PH5, PH7, PH11, SH3	G1, H1, H3	O1, O4	58
(Åström et al., 2014)	Develop a risk assessment and decision support framework for pluvial urban flood risk under non-stationary conditions using an influence diagram	PH7, SH3	H3	O1	59
(Oswald & Treat, 2013)	Assess the vulnerability of public transportation infrastructure to sea level rise in Philadelphia County, Pennsylvania	PH11, SH4	H1, H2, H3	–	60
(Palin et al., 2013)	Assess the impact of temperature-related climate change on Great Britain's railway network for future planning and adaptation	PH2, PH3	S1	O1, O7, O11, O13	61
(Nguyen et al., 2012)	Assess the reliability of railway track buckling during extreme heatwave events for future planning and management	PH2	S1	–	62
(Larsson-Kräik, 2012)	Perform a cost-benefit-risk analysis to manage avalanche risks and improve safety on the Malmaban (Swedish Iron Ore Line)	PH5, PH7, SH7	–	O1, O4, O14	63
(Dobney et al., 2010)	Quantify the effects of higher summer temperatures due to climate change on the UK railway network	PH1, PH2	S1	O1	64
(Clarke & Smethurst, 2010)	Assess the impact of climate change on the cycles of wetting and drying in engineered clay slopes in England	PH7, PH12, SH5, SH6	G1, G3, G6	–	65
(Snoussi et al., 2009)	Assess the vulnerability of Tangier Bay to sea-level rise and propose adaptation strategies	PH11, SH4	H2, H3	–	66
(Lindgren et al., 2009)	Assess the vulnerability of the Swedish railway system to climate change and investigate the adaptive capacity of the current system	PH1, PH7, PH10	S1, G4	O8, O14	67
(Geertsema et al., 2009)	Provide examples of various types of destructive landslides impacting linear infrastructure and consider future landslide potential under climate change scenarios	PH7	G1	O4	68
(Dobney et al., 2009)	Quantify the effects of high summer temperatures due to climate change on buckling and rail-related delays	PH1,	S1	O1, O14	69
(Manning et al., 2008)	To examine the susceptibility of a transport system to rainfall-induced landslides under current and future climate scenarios	PH7	G1, G4	O14	70
(Garg et al., 2007)	Develop a framework for integrating impact assessment and adaptation responses in India, focusing on railway coastal infrastructure	PH1, PH7, PH11	H2	O1	71

Data availability

Data will be made available on request.

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