Environmental Research Communications

OPEN ACCESS

RECEIVED
4 July 2025

REVISED
27 February 2026

ACCEPTED FOR PUBLICATION
14 April 2026

PUBLISHED
6 May 2026

TOPICAL REVIEW

The potential effects of heat extremes on educational outcomes of children in low- and middle-income countries: a systematic review

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Keywords: climate change, extreme heat, educational outcomes, school-going children, low- and middle-income countries (LMICs)

Supplementary material for this article is available online

Abstract
Heat extremes related to climate change increase the exposure of children to non-optimal learning environments, which may threaten children's educational achievement and a country's sustainable development, especially in low- and middle-income countries (LMICs). This is a systematic review of quantitative evidence on the potential effects of extreme heat on the educational outcomes of children in LMICs and on the potential causal pathways of such effects. The review is guided by a pre-specified registered protocol (ID: PROCEED-24-00313). We systematically searched electronic databases up to 23 September 2024 (no date limits), supplemented by open searching, reference mining, hand searching and articles from content experts. We critically appraised studies for risk of bias. The heterogeneity of the studies precluded a pooled estimate of effect. We present a narrative synthesis of the effects of heat extremes on educational outcomes, and we include modifying factors and causal pathways of these effects. Negative effects of heat were reported for academic performance in both mathematics and verbal test scores, with mixed effects for high-stakes university entrance examinations. Heat had potential negative effects on school completion and attendance. Mediating factors included gender, education and socio-economic level, urban/rural location and building characteristics. Potential causal pathways included the direct effects on a learner's learning ability through physiological and cognitive stress, and the indirect effects on access to education via the loss of livelihoods, especially in poorer agrarian communities. There is evidence of potential negative effects of heat on academic performance in particular, although the range in the effect size and mediating factors highlight the complexity of the relationship between extreme heat and educational outcomes. Policies may be needed for the provision of climate-resilient education infrastructure and learning systems, and for social safety nets to attenuate economic vulnerability. More evidence is needed, especially on what multiple dimensions are needed for climate-resilient adaptation.

1. Background

The United Nations sustainable development goal 4 recognises access to good quality education as a universal human right, and a key to escaping poverty (United Nations Department of Economic and Social Affairs 2016). Climate change poses a threat to educational advancement and to sustainable development, especially in low- and middle-income countries (LMICs) (Caruso *et al* 2024), and can affect poverty and inequality through its impacts on labour productivity and human capital (Dang *et al* 2024). Learners from LMICs are disproportionately affected by heat extremes, owing to existing structural vulnerabilities such as a lack of basic infrastructure; for instance, learners may lack ventilation, cooling and reliable water and energy supplies (Tschakert *et al* 2025, Zamir *et al* 2026). Heat extremes may reinforce existing vulnerabilities in socio-economically disadvantaged populations (Assari and Zare 2024). The increased occurrence and severity of climate-related impacts on schools and learners means the increased exposure of children to sub-optimal and unsafe learning environments, which can compromise the quality of learning and reduce children's access to education. For example, floods, droughts and heatwaves are occurring much more frequently compared to 40 years ago and are disrupting learning for an estimated 40 million children each year (United Nations Children's Fund [UNICEF] 2023).

The impacts of climate change and extreme weather events, such as wildfires, extreme heat, cyclones, storms and floods, have caused loss and damage to housing, livelihoods and social stability, while worsening inequalities (Intergovernmental Panel on Climate Change [IPCC] 2022). Heat-related mortality and morbidity are projected to increase worldwide (Intergovernmental Panel on Climate Change [IPCC] 2022). With current policies placing the world on a path toward roughly 2.7 °C of warming, today's children are likely to experience far more frequent and intense heatwaves, droughts, floods and other hazards over their lifetimes than earlier generations. (Intergovernmental Panel on Climate Change [IPCC] 2022, Grant *et al* 2025). Around one-third of the world's children were exposed to heatwaves in 2020 (United Nations Children's Fund [UNICEF] 2021b), and this intergenerational gap is projected to widen as climate warming leads to more frequent, intense, and prolonged heat events (Thiery *et al* 2021). Warmer climate settings, including many LMICs, are facing higher exposures to extreme heat conditions and, as a result, are experiencing the greatest burden on education outcomes (Marin *et al* 2024), which highlights the need for more evidence on the effects of heat on education outcomes in these settings. A meta-analysis of classroom temperature and learning found that lowering temperatures from 30 °C to 20 °C improved student performance by about 20%; optimal learning conditions were below 22 °C. Most of the underlying studies, however, were from temperate climates, with limited evidence from the tropics and/or LMICs contexts (Wargocki *et al* 2019). The experience of heat can have different effects on populations, schools and students across and within countries, as resilience to these stressors is determined by prevailing socio-economic conditions and the availability of resources (Marin *et al* 2024). Further robust systematic review evidence from different contexts is needed to understand the potential effect that climate change–related extreme weather events like heat have on educational outcomes of children (Pankhurst 2022, Leal Filho *et al* 2023, Abuya *et al* 2024, Marin *et al* 2024).

There is growing recognition in primary research of the negative effects of climate hazards on educational outcomes (Leal Filho *et al* 2023, Caruso *et al* 2024). Although nascent, there is growing evidence on the potential adverse effects of extreme heat on educational outcomes. Potential underlying causal pathways informing our research question draw on published evidence of the relationship between high temperatures and educational outcomes (Feinstein and Mach 2019, Lassa *et al* 2023, Reyes and Randell 2023, Pazos *et al* 2024). Extreme heat can affect education in at least three ways. In figure 1, we use the context-mechanism-outcome framework (Rycroft-Malone *et al* 2015) as the structure for this logic model, and we draw on the education and social science literatures to illustrate the three commonly discussed potential pathways, that is, via direct, indirect and vicarious effects (Feinstein and Mach 2019, Hayes *et al* 2020, Léger-Goodes *et al* 2022, Lassa *et al* 2023, Reyes and Randell 2023, Pazos *et al* 2024).

Like other disasters, heat waves affect the most vulnerable population groups and systems disproportionately, particularly across LMICs (Cissé *et al* 2022). The effects are threefold. First, extreme heat exposure directly affects learners' cognitive capability as well as the physiological and psychological determinants of learners' resilience (Feinstein and Mach 2019, Reyes and Randell 2023, Pazos *et al* 2024). Second, climate hazards affect education outcomes indirectly through, for example, flood damage to education infrastructure such as roads, schools and internet facilities (Lassa *et al* 2023). Extreme heat exposure can have medium- to long-term effects on livelihoods through reduced agricultural production and degraded environmental and socio-economic assets, thereby increasing poverty and having the associated adverse indirect effect on educational access and attainment (Feinstein and Mach 2019, Reyes and Randell 2023, Pazos *et al* 2024). Another indirect effect is heat-related illnesses and negative health implications that reduce functioning and constrain households' ability to generate a stable income for

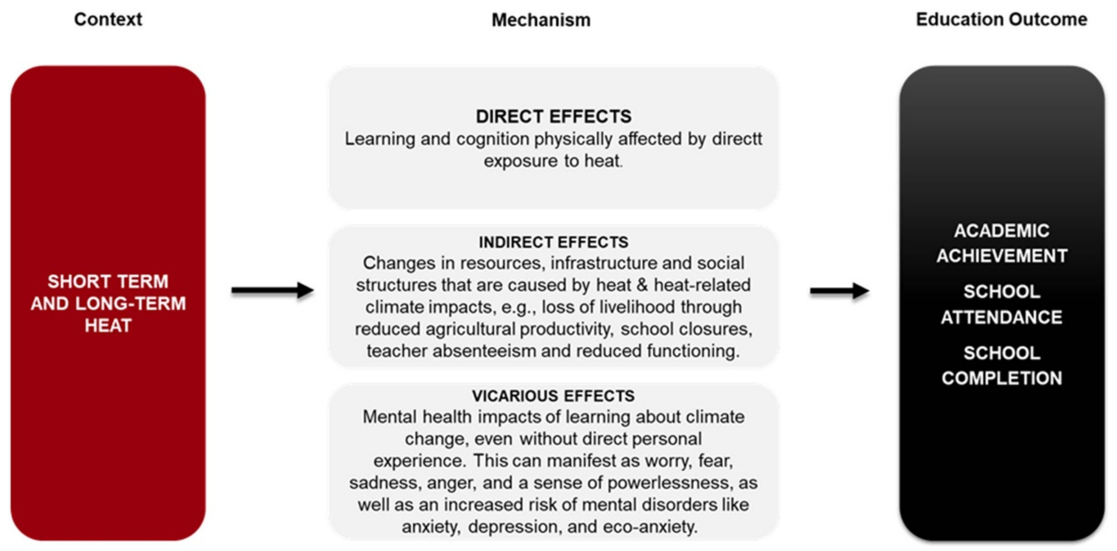

Figure 1. Logic model for the potential impact pathways of heat on education outcomes.

sustenance. This could result in food insecurity (Arnell *et al* 2014, Zivin and Shrader 2016), and associated limits to educational access and attainment (Park 2022, Leal Filho *et al* 2023). Third, heat can have vicarious mental health effects from learning about climate change, even without direct personal experience (Hayes *et al* 2020, Léger-Goodes *et al* 2022). These effects can manifest as worry, fear, sadness, anger and a sense of powerlessness, and increase the risk of mental disorders like anxiety, depression, and eco-anxiety, which have potentially negative effects on learning and education (Hayes *et al* 2020, Léger-Goodes *et al* 2022).

Education is increasingly viewed as a tool to enhance resilience to climate shocks and support adaptation efforts (Mazari *et al* 2022). Education empowers children and young people with access to opportunities, including the knowledge and ability to sustainably adopt climate-smart socioeconomic activities (Leal Filho *et al* 2023). Furthermore, formal education contributes to employment creation and poverty reduction. The impacts of climate change therefore threaten not only schooling outcomes but also a person's lifelong learning capacity and social well-being more broadly (Randell and Gray 2019, Intergovernmental Panel on Climate Change [IPCC] 2022). Even so, compared to evidence of climate-change effects on health (Lakhoo *et al* 2025), there is less evidence on the potential effects of climate change on education, including for heat extremes. The need for evidence and policies dealing with the potential effect of heat extremes on education outcomes is particularly urgent for LMICs, many of which are at high risk of heat extremes due to their geographical location in the tropics, their economic structural vulnerabilities and data gaps (Randell and Gray 2019, Pankhurst 2022).

Robust synthesised evidence on the effect of climate change–related environmental shocks is needed to inform policymakers on how the education sector can adapt and deal with loss and damage related to climate change (Abuya *et al* 2024, Marin *et al* 2024). Several existing reviews focus broadly on climate change and its effects on education (Pankhurst 2022, Leal Filho *et al* 2023, Prentice *et al* 2024) but reviews on heat specifically (and especially for LMICs) are scant. To our knowledge, there is not yet a systematic quantitative review on the effects of heat on children's educational outcomes in LMICs, yet heat is a common climate-change risk in many LMICs, especially in the tropics (Randell and Gray 2019, Pankhurst 2022).

While there are some overlaps, existing reviews differ from ours in scope and methodology. For example, a grey literature report by Pankhurst (2022) conducted a review on the diverse and complex ways in which girls' education and climate change intersect. Pankhurst found evidence of a relationship between girls' education and climate change in LMICs, acknowledged the limited and inconsistent evidence base, and called for further, rigorous research across diverse contexts. Our review differs from the Pankhurst review as it includes all genders, focuses only on heat and employs a systematic review methodology. Leal Filho *et al* (2023) conducted a qualitative review of research articles about and case studies of initiatives to support the efforts of children to adapt to climate change and how such child-centred approaches can strengthen the resilience of households and communities. Our review differs from that of Leal Filho *et al* as ours synthesises only quantitative evidence. Zivin and Shrader (2016) focused on heat only when they examined the ways in which rising temperatures from global warming can cause death among foetuses, young children and the elderly. Their review highlights the importance of humidity in combination with high temperatures and they postulate about the potential effects rather than observed effects of heat on education outcomes.

Two more directly relevant reviews provided useful stepping stones for our review. The first is a cross-disciplinary review of how climate stressors (such as floods, heat, wildfires, storms, drought, vector-borne diseases and rising sea-levels) have affected children's education outcomes worldwide (Prentice *et al* 2024). The second is a quantitative review on how extreme weather events impact education outcomes, based on a study conducted for the World Bank (Marin *et al* 2024). Both these reviews are global and consider multiple climate events, while our review focused on LMIC and only on heat. These two reviews did not follow standard robust systematic review methodology, but they included useful articles on heat in LMICS that our review could draw on.

Our review responds to this gap in robust systematic review methodology by synthesising data relevant to the following research question: 'What are the potential effects of heat extremes on educational outcomes of children in LMIC countries, and what are the potential causal pathways of effect?' Estimating the adverse effects and understanding the impact pathways of extreme heat provide a deeper understanding of the problem and can inform appropriate adaptation strategies for the education sector to respond adequately to climate change–related challenges.

2. Methods

We conducted a systematic review of quantitative evidence on the potential effects of heat extremes on children's educational outcomes in LMICs and the suggested mechanisms of effect and causal pathways. This systematic review was conducted following a pre-specified protocol registered in PROCEED (PROCEED-24-00313), and the results are reported using the ROSES guidelines.

2.1. Inclusion and exclusion criteria

We used the PECOS format (Morgan *et al* 2018) to formulate our question and inclusion criteria, as shown below.

The **population (P)** for this study is the educational sector in LMICs as defined by the World Bank (World Bank 2022). The focus was on children of school-going age from preschool to secondary school. Age ranges may have varied across countries, so we anticipated the age range to be between 4 and 20 years.

The **exposure (E)** is exposure to heat extremes. Indicators were comparatively high heat or 'hot days', rising temperatures over time, extreme heat events such as heat waves and the urban heat-island effect.

Comparison (C) was the quantitative effects compared to effects during periods of lower and/or more average recorded temperatures.

Outcomes (O) included a range of educational outcomes such as academic performance, school attendance, school access, retention, completion, cognitive abilities, literacy, and numeracy.

The **study designs (S)** eligible for inclusion were primary, quantitative studies of the effects of heat and educational outcomes of children.

We excluded evidence for children that were not of school-going age and for young people in tertiary education. We also excluded evidence of effects of other related environmental stressors, such as wildfires and extreme cold temperatures, as well as other stressors, such as pollution, earthquakes, and floods. We excluded qualitative primary studies as our focus was on extracting quantitative effects. We excluded secondary studies providing synthesised evidence (reviews) but used these for data mining to identify potential primary studies that might have been missed. We wanted to focus on robust peer-reviewed evidence only, so we excluded grey literature. For logistical reasons of time and researcher capacity, only peer-reviewed studies published in English were included.

2.2. Data search approach

Systematic searching was done on 23 September 2024, and supplementary searches were done up to 28 November 2024. The best electronic databases to search were determined in consultation with a library information specialist and further developed iteratively from reviews of empirical studies. Furthermore, the search strategy with appropriate search terms was developed in consultation with the librarian information specialists. Pilot searches showed that there was not much literature on the topic, so we did not include a search filter for year of publication.

We used the following databases in our search for peer-reviewed articles: Scopus, Web of Science and EBSCO host (Academic Search Premier, Africa-Wide Information, Biological & Agricultural Index Plus (H.W. Wilson), ERIC, General Science Abstracts (H.W. Wilson), Humanities International Complete, PA PsycArticles, APA PsycInfo, SocINDEX with Full Text, Teacher Reference Centre). The databases were selected based on their subject coverage. We included Scopus and Web of Science for their interdisciplinarity and broad coverage across the sciences and social sciences. In addition, using subject-specific databases available through EBSCOhost, we focused on education, social sciences, psychology, and climate. These databases speak to individual disciplines that impact this area of research and offer complementary insights into the topic. The full electronic search string for each academic database can be found in supplementary file 1. The generic search terms used for searching academic databases were:

('Climate change' OR 'global warming' OR 'High temperatures' OR 'heat' OR Heatwaves OR 'Extreme temperatures' OR 'Hot weather')

AND

('Educational attainment' OR 'Academic performance' OR 'Test scores' OR 'Class participation' OR 'School dropout' OR 'School closure' OR 'class disruption' OR 'school disruption' OR 'human capital' OR 'student time allocation' OR 'cognitive function' OR 'cognitive development' OR 'educational outcome' OR 'school performance' OR 'literacy' OR 'numeracy' OR 'school infrastructure' OR 'socio-emotional learning')

AND

('child*' OR 'adolescen*' OR 'high school' OR 'primary school' OR 'secondary school' OR 'elementary school' OR 'middle school' OR 'preschool' OR 'kindergarten')

We practised with several initial exploratory search strings during the development of the protocol, and we used these practice rounds for iterative improvements and testing of pilot search strings. Our first pilot search was to identify eligible articles. We found only three studies, which we used as benchmark articles to build a comprehensive search strategy. These articles were sent to the librarian together with a draft search string. Two additional pilot searches were conducted, and they identified two out of the three benchmark studies. The search string was adjusted, and hand searching was included as an additional search strategy. To increase the comprehensiveness of the search, we supplemented our systematic search with open searching in Google scholar, reference mining, handsearching and eliciting articles from content experts in the team.

2.3. Data screening

All records returned from academic literature searches were first imported into EndNote, a reference management tool. The results from the search were then uploaded to Covidence (www.covidence.org/), which is a systematic review management software tool for screening relevant articles. All duplicated records were automatically identified and removed, first in EndNote and then in Covidence. Covidence, we screened titles and abstracts, and full texts, based on the inclusion and exclusion criteria. Studies were included if they adhered to our target population (children of school-going age, from LMICs), if they measured the effect of extreme heat (exposure) on educational outcomes, and if the study design was suitable for estimating quantitative effects. Studies that assessed the effects of multiple weather events, such as a combination of heat and rainfall, were only included if they reported the effects of heat separately from the effects of other weather events.

To standardise the screening of titles and abstracts, four authors (PN, MP, IS and NL) pilot-screened the studies. The first 20 studies were screened independently by two authors, and we then met to compare decisions. A third author acted as a referee to resolve conflicts. After our first discussions, we conducted another round of blind screening on 30 additional studies. This was done to ensure that all co-authors understood the inclusion–exclusion criteria and to minimise conflicts in assessment. Conflict resolution was facilitated by discussion between the two conflicting authors; failing resolution, the third author decided whether to include or exclude an article. After this process, all four authors conducted full text screening. The same approach of independent, parallel, duplicate screening and conflict resolution was followed during the full-text screening.

2.4. Data extraction

We developed a de novo data-extraction template that shows the categories of information pertinent to our research question (see supplementary file 2). Four reviewers (PN, MP, IS and NL) extracted data from the 11 eligible studies using this data-extraction template. For each study, two reviewers extracted data independently. In addition, the senior reviewer (NL) checked 50% of the work of the other reviewers, in order to improve the standardisation and accuracy of the data extraction.

In an excel version of the data-extraction template, we captured study characteristics such as author, year, title; population and sample size; the measure of heat exposure; and the educational outcomes measured (results on the size and direction of the effect for all educational outcomes listed). Outcomes were disaggregated by age, gender, geographical location, household income, etc., where this information was available. Causal mechanisms described by study authors were recorded.

2.5. Data analysis and synthesis

The studies were too heterogeneous (see 'Description of included studies') to allow for pooled estimates. We therefore conducted a descriptive narrative synthesis of quantitative effects, in which we describe the effects reported in the studies, and highlight statistics on the size and direction of effects, as well as sub-analyses of multiple variables.

For the narrative synthesis of the main findings, we summarised information within and across the categories we used in our data-extraction template. This information included the characteristics and the quantitative findings of the studies. For the main findings on the effect of heat, we grouped together studies with similar educational outcomes (e.g. mathematics and verbal test scores; school completion). We provided an overview of the trend seen across the studies for each outcome, followed by a summary of findings for the individual studies. Drawing on sub-analysis data, we identified a number of modifying variables across studies and described these within the context of individual studies.

For our secondary question on mechanisms or potential causal pathways, we provide a narrative description of association, which we based on the quantitative data from the studies, and on interpretations by the studies' authors where this information was available. We describe the main suggested causal mechanisms and provide a diagrammatic illustration of these mechanisms.

3. Findings

A total of 1031 records (titles and abstracts) were identified through systematic searching of electronic databases and using supplementary search strategies. In figure 2, the ROSES flow diagram shows the identification and inclusion of records. After removing duplicates, 929 records were screened. Of these, 100 papers were identified as eligible for full-text screening. Eleven studies were eligible for inclusion while 87 were excluded. We could not retrieve full texts of two studies. The reasons for exclusion are listed in the ROSES flow diagram (Haddaway *et al* 2017) and were mostly due to ineligible study designs, exposure and outcomes.

3.1. Description of included studies

A detailed description of the included studies is shown in table 1. Details include first author, year, study title, country, population, sample size, study design, data sources, type of heat measured and study outcomes measured.

3.2. Publication date and funding sources

A total of 11 studies, published from 2016 to 2024, were included; all except one were published recently from 2019 to 2024. Seven studies reported their funding sources, which included academic institutions (e.g. the National Natural Science Foundation of China) and global development initiatives (e.g. the Environment for Development initiative) and four studies did not disclose funding information. Six studies did not report on conflicts of interest.

3.3. Geographic distribution

As shown in table 1, geographically, eight studies focused on single countries, including two from China (Zivin *et al* 2020, Zhang *et al* 2023), and one each from South Africa (Pule *et al* 2021), India (Garg *et al* 2020), Mexico (Arceo-Gomez and López-Feldman 2024), Ethiopia (Randell and Gray 2016), Vietnam

Table 1. Characteristics of included studies.

First author	Year	Title	Low- and middle-income country	Study design	Population	Sample size	Data sources	Type of heat measured	Outcomes measured
Arceo-Gomez	(2024)	Extreme temperatures and school performance of the poor: evidence from Mexico	Mexico	Fixed-effects panel data design using ENLACE standardised test scores (for Spanish and mathematics)	11–15 years old	5.5 million students	ENLACE-Prospera 2007 data from 2007 to 2013 ERA-Interim weather data from 1979 to 2013 www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim	Average temperature and precipitation over 365 d pre-examination, and temperature anomalies based on deviations from long-term (1979–2000) monthly means Municipalities were classified as hot, cold, or temperate by historical temperature percentiles.	Test scores: Spanish and Mathematics
Delprato	(2024)	Climate change and its impact on education completion rates across four sub-Saharan African countries: a non-parametric approach at the community level	Cameroon, Ethiopia, Guinea and Nigeria	Ecological study design (Community-level analysis using a non-parametric approach)	Children and youth (no age range given)	2,527 communities (Cameroon = 412, Ethiopia = 557, Guinea = 311, Nigeria = 1247)	Demographic and Health Surveys from 2016 to 2018 Aridity (aridity index-AI), land surface temperature, rainfall and the enhanced vegetation index measured in 2015, and for EVI—1985–2015,	Aridity (a combined indicator of temperature and rainfall) Land surface temperature Rainfall data Enhanced vegetation index: rates of vegetation change were calculated as a measure of long-term ecosystem stress	Completion rates at primary, lower- and upper-secondary and tertiary levels
Zhang	(2023)	Temperature and low-stakes cognitive performance	China: 162 counties in 25 provinces	Longitudinal study using fixed-effects regression models	Cohorts 10–20 years old and older (up to 60 years old)	Used 70 736 observations (out of 96 990 observations in the study) matched to weather data	Test scores: China family panel studies dataset from 2010 to 2018. Weather data: China national meteorological data service centre data from 2014 to 2018	1. Division of daily mean temperatures into 12 bins, with the lowest bin including all temperatures below 12 °C and the highest bin including all temperatures above 32 °C, on test dates 2.Cumulative effects (the number of consecutive heat-wave days immediately before the survey, and the longest consecutive heat-wave days in the past month)	Mathematics test scores (24 standardised mathematics questions) Verbal test scores (32 word-recognition questions)

(Continued.)

Table 1. (Continued.)

First author	Year	Title	Low- and middle-income country	Study design	Population	Sample size	Data sources	Type of heat measured	Outcomes measured
Vu	(2022)	Effects of heat on mathematics test performance in Vietnam	Vietnam	Ecological study design (entrance examinations linked with the daily weather summaries)	Students who took the national university and college entrance examinations	294 623 test-takers	Higher education department, ministry of education and training of Vietnam in 2009 US national oceanic and atmospheric administration from 1950 to 2009	Daily temperature and precipitation data with the test-day average temperature as the main independent variable	Mathematics test scores: Standardised mathematics test scores (Z-scores) for mathematics tests that were compulsory, uniformly structured and administered at fixed times across all examination dates. Log-transformed scores were also used for robustness checks.
Pule	(2021)	Classroom temperature and learner absenteeism in public primary schools in the Eastern Cape, South Africa	South Africa	Mixed-effects negative binomial model	Public primary school learners	30 schools	Absenteeism data from 2017 to 2018 were collated in Microsoft Excel Indoor classroom temperature and humidity: iButton/Lascar temperature and relative humidity dataloggers from 2017 to 2018 Outdoor temperature and humidity: South African Weather Service's Bhisho Weather Station from 2017 to 2018	Mean indoor classroom and outdoor temperatures; relative humidity and windspeed data	Learner absenteeism: A daily attendance sheet in the form of daily records or counts of absent learners (absenteeism counts per day)

(Continued.)

Table 1. (Continued.)

First author	Year	Title	Low- and middle-income country	Study design	Population	Sample size	Data sources	Type of heat measured	Outcomes measured
Park	(2021)	Learning is inhibited by heat exposure, both internationally and within the united states	Wide range of incomes and average climates in Vietnam, Thailand, France, New Zealand and South Korea	Quasi-experimental research designs	15–19 years old	144 million students	Programme for international student assessment (PISA) test scores data from 2000 to 2003	Daily maximum and minimum temperatures and total daily precipitation Exposure was based on counts of days falling into temperature bins (bins ranged from—17.7 °C to 60 °C in 5.5 °C intervals). The National Oceanic and Atmospheric Administration's Global Historical Climatology Network from 1995 to 2015	Combined test score: Average combined PISA score (mathematics, science, reading) by country
Li	(2021)	Weather and high-stakes examination performance: evidence from student-level administrative data in Brazil	Brazil	Ecological study design	Students between the ages of 14 and 22, who wrote college entrance examinations	947 512 test-takers	Exame Nacional do Ensino Médio, known as ENEM from 2012 to 2016 Weather data from the nearest weather stations (in Brazil) from 2012 to 2016	Dry bulb temperature: (heat, humidity, rainfall, aridity) on two test days as well as seven days before the first test day.	Combined test score of several subjects, namely humanities, natural sciences, languages, mathematics and writing

(Continued.)

Table 1. (Continued.)

First author	Year	Title	Low- and middle-income country	Study design	Population	Sample size	Data sources	Type of heat measured	Outcomes measured
Zivin	(2020)	Temperature and high-stakes cognitive performance: evidence from the national college entrance examination in China	China	Regression analysis	High school students taking the national university and college entrance examinations	14 million students	National College Entrance Examination from 2005 to 2011 http://gaokao.com/ China meteorological data service Centre. Two days during the examinations each year from 2005 to 2011 www.sciencedirect.com/topics/social-sciences/meteorological-data National Oceanic and Atmospheric Administration of the U.S.A. www.sciencedirect.com/topics/earth-and-planetary-sciences/united-states-of-america	Average mean temperature during the examination period: 1. Degree Days (DD): A linear measure that calculates how many degrees the daily temperature is above or below a threshold of 14 °C. 2.Temperature Bins: A non-linear measure using 2 °C intervals; bins range from below 12 °C to above 28 °C to account for data sparseness at the extremes.	Combined test score: Total test score comprising scores from three compulsory subjects worth 150 marks each plus score from one elective subject worth 300 marks
Garg	(2020)	Temperature and human capital in India	India	Repeated cross-sectional design combined with a longitudinal panel	School-age children in primary and secondary education	4.5 million students	The Annual Status of Education Report (ASER) from 2006 to 2014 The Young Lives Survey (YLS) from 2002 to 2011 Weather: ERA-Interim daily temperature and precipitation data from 1979 to present day	Daily average temperature, daily total rainfall, and daily mean relative humidity	Test scores: ASER tests are brief (up to four questions in mathematics and reading) YLS tests are longer (30 mathematics, ∼100 reading questions) and provide household socioeconomic and health data

(Continued.)

Table 1. (Continued.)

First author	Year	Title	Low- and middle-income country	Study design	Population	Sample size	Data sources	Type of heat measured	Outcomes measured
Randell	(2019)	Climate change and educational attainment in the global tropics	Global tropics: 29 countries across the global tropics in sub-Saharan Africa, Latin America and the Caribbean, Southeast Asia, and West and Central Africa	Ecological study (observational and longitudinal)	Children born in 1950 or later, who were 12–16 years old at the time of the census	13 831 770 observations from 85 censuses conducted between 1969 and 2012	Education: social data from the Integrated public use microdata series-international, from 85 censuses conducted between 1969 and 2012 Weather: The Climatic Research Unit Time-Series (CRU TS v. 4.00) data: monthly gridded mean temperature and precipitation data from 1900 to the present	Early-life mean annual temperature and total annual rainfall anomalies (z-scores) from the year before birth to age five	Highest grade/level of formal schooling completed, measured in years
Randell	(2016)	Climate variability and educational attainment: Evidence from rural Ethiopia	Ethiopia	Longitudinal survey	Children in rural farming households who were 12–16 years old	3336 individuals from 1227 households, across 15 villages	Test score: Ethiopian Rural Household Survey from 1994 to 2009 Climate Research Unit Time-Series data from 1970 to 2009	Seasonal temperature and rainfall variability measured as *z*-scores relative to 1970–2009 norms; classified as hot/cold or wet/dry based on thresholds ($\pm$1SD) for spring rainy season, summer rainy season, and winter dry season	Schooling outcomes: Whether the child completed at least one grade and attended school during the survey year, and a categorical variable for total number of grades completed (0, 1–4, 5–12 yrs)

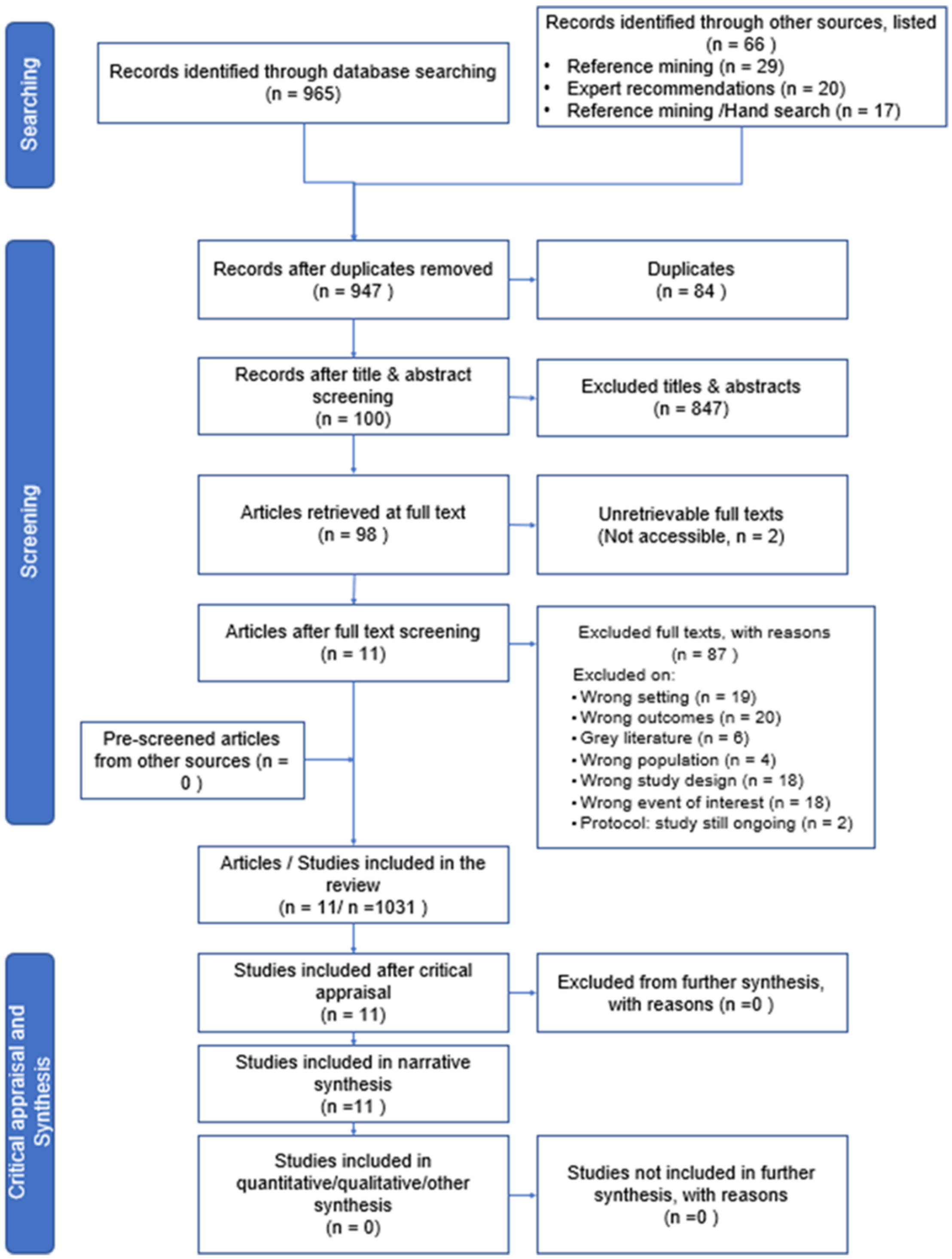

Figure 2. ROSES flow diagram of identification and inclusion of records for extraction. Reproduced from Haddaway *et al* (2017). CC BY 4.0.

(Vu 2022) and Brazil (Li and Patel 2021). Three were multi-country studies, with one covering 29 tropical countries (countries across sub-Saharan Africa, Latin America and the Caribbean, Weste and Central Africa, and Southeast Asia) (Randell and Gray 2019); one covering four African countries (Cameroon, Ethiopia, Guinea, Nigeria) (Delprato and Shephard 2024); and another examining countries across diverse income levels and climates (Vietnam, Thailand, France, New Zealand, South Korea. In the latter study, we extracted data for only the two LMICs, Vietnam and Thailand) (Park *et al* 2021).

3.4. Study design

All the studies were quantitative in design. Most of the study designs were not explicitly labelled but can be categorised as ecological because they focused on population-level associations of the effects of weather events, by drawing on large data sets of weather events (heat) and data sets of educational outcomes.

3.5. Target population

The target populations of the studies differed in age groups and educational contexts. Studies examined school-going children and youth in primary and secondary school, as well as students preparing for college entrance examinations, with ages in the range of 5–20 years. Few studies included school-going children across both primary and secondary levels, while most studies focused on students of 10 years and older and on one education exit point (e.g. university entrance examinations). One study (Zhang *et al* 2023) included a broader age range of 10 to over 60 years old; we extracted data from this study for school-going children between the ages of 10 and 20 years as this was the closest match in age to our target group. Another study explored schooling outcomes at the community level, by analysing completion rates at primary, lower secondary, upper secondary and tertiary levels in four sub-Saharan African countries (Delprato and Shephard 2024).

The studies reported a wide range of sample sizes, which ranged from as large as 144 million participants in the international Programme for International Student Assessment (PISA) (Park *et al* 2021) to as small as 979 respondents in one country (Pule *et al* 2021). One study included community-level analyses of 2,527 communities across four countries (Delprato and Shephard 2024) and another covered larger datasets with more than 14 million observations (Zivin *et al* 2020).

Six studies reported on gender (Randell and Gray 2016, Zivin *et al* 2020, Li and Patel 2021, Vu 2022, Arceo-Gomez and López-Feldman 2024, Delprato and Shephard 2024) and six studies reported on socio-economic factors (Garg *et al* 2020, Zivin *et al* 2020, Park *et al* 2021, Vu 2022, Arceo-Gomez and López-Feldman 2024, Delprato and Shephard 2024).

3.6. Description of heat exposure

Although all 11 studies were on heat exposure, some included other environmental events. Five studies focused exclusively on the effects of heat (Garg *et al* 2020, Park *et al* 2021, Vu 2022, Zhang *et al* 2023, Arceo-Gomez and López-Feldman 2024). Six studies investigated heat together with other environmental or weather events, such as rainfall, humidity, aridity and the effects of air pollution (Randell and Gray 2016, 2019, Zivin *et al* 2020, Li and Patel 2021, Pule *et al* 2021, Delprato and Shephard 2024). In these combined weather-event studies, we focused on the effects of heat and, where relevant, only reported combined effects as additional information to enhance understanding of the heat effects.

The time periods and spatial coverage for the measurement of the exposure to heat were different across the studies. While some studies measured daily temperature on the day of testing (e.g. Randell and Gray 2019, Zhang *et al* 2023), others measured changes in average monthly or annual temperature before the test was taken, and/or an accumulation of days with above-average heat or different ranges of temperature (temperature 'bins') or long-term changes in annual temperatures (Arceo-Gomez and López-Feldman 2024). Specific measures of temperature also varied across studies, including the use of an average temperature (Arceo-Gomez and López-Feldman 2024), mean temperatures (Randell and Gray 2019, Pule *et al* 2021, Zhang *et al* 2023), and a temperature range, i.e. a minimum and a maximum temperature (Zivin *et al* 2020).

Furthermore, the timing of the exposure also varied in relation to the outcome. Some studies considered short-term, acute effects of heat exposure on school performance, such as heat exposure during the time that examinations or tests were taken (Vu 2022, Zhang *et al* 2023), while other studies measured medium-term and cumulative effects by recording temperatures for 365 d or three years before examinations or tests (Garg *et al* 2020, Arceo-Gomez and López-Feldman 2024). One study considered the long-term effects of heat exposure in utero and early childhood, and its effects on school performance (Randell and Gray 2019).

Zivin *et al* (2020) noted that contemporaneous temperature effects, especially daily maximum temperatures, showed a statistically stronger effect than other heat measures such as mean temperatures or temperature bins, or longer temperature exposures (e.g. for the year before the examination). None of the other studies provided information on which heat measures were more effective at accurately measuring the impact on educational outcomes.

3.7. Description of educational outcomes

Across the 11 studies, three different types of educational outcomes were assessed. These were academic performance, school attendance and school completion. All except one of the studies examined only one of these three types of educational outcomes; Randell and Gray (2016) explored both completion and attendance. The seven studies that examined academic performance focused on test scores only (Zivin *et al* 2020, Li and Patel 2021, Park *et al* 2021, Vu 2022, Zhang *et al* 2023, Arceo-Gomez and López-Feldman 2024). The scores were for mathematics tests and for verbal, reading and language tests (referred to as 'verbal' for ease of reading, unless otherwise stated). Three studies reported the effects of high temperatures on a single test score that was a combined test/examination score of several school subjects (Zivin *et al* 2020, Li and Patel 2021, Park *et al* 2021). Two studies (Randell and Gray 2016, Pule *et al* 2021) focused on school attendance by measuring learners' absenteeism. Three studies reported the effect of heat on children's school completion in the form of the highest grade/level completed and the rates of school completion (Randell and Gray 2016, 2019, Delprato and Shephard 2024). In most of the studies, countrywide databases for academic performance on standard testing were used.

Besides reporting the main outcomes, the studies also reported on a range of sub-analyses of outcome variables, from as little as one additional variable (Pule *et al* 2021) to as many as six additional variables (Zivin *et al* 2020). The variables used in the sub-analysis across these studies can be grouped into the following three categories:

1. Demographic and geographic variables (e.g. gender and age of participants; geographical location such as urban/rural; historical temperatures; hotter/wetter provinces; rainfall).
2. Socio-economic variables (e.g. educational level and/or occupation of the household head; levels of community disadvantage such as poverty levels and marginalised municipalities).
3. Variables related to the characteristics of school buildings (e.g. quality of the infrastructure of the classroom building; presence of air-conditioning).

We did not find eligible studies on the effects of extreme heat on the rates of dropping out from school or school enrolment. Nor did we find indirect effects, such as heat-related school closures, reduced school functioning or teacher absenteeism, on the educational outcomes of children. None of the selected studies covered vicarious effects such as climate change–related anxiety and mental-health stress.

3.8. Critical appraisal of the studies

The critical appraisal of the quality of these studies was based on the data-analysis methods employed in the studies to allow for the causal interpretations and efficiency of the estimates of effect. To evaluate the studies on a standardised scale, the statistician in the team ((MM) modified and applied the tool developed by Konno *et al* (2021). The original tool was not compatible with the study designs of all our reviewed studies; hence, we modified the tool to suit the study designs of our reviewed studies. The appraisal used ten criteria and a 5-point Likert Scale ranging from 'very low' to 'very high' bias levels. The very low rank indicates the most credibility, while very high bias estimates indicate that a higher level of caution should be taken when interpreting causal claims. The criteria used for our bias assessment were: confounding bias, identification strategy (endogeneity from the feedback effect), autocorrelation (cluster or serial or spatial), stationarity (where a time series, or a variable such as temperature or test score, has a constant average, variance or pattern over time, measurement error in the dependent variable, measurement error in the independent variable, robustness checks and selective reporting bias. The overall rating was taken as the maximum (worst) rank of all ten criteria, unless otherwise explained. For more details on the critical appraisal method and analysis, see supplementary file 3 that shows the critical assessment scores for each study. Details of the analysis approach can be found in supplementary file 4: critical appraisal of studies—analysis.

All the reviewed studies ranked 'very low bias' in terms of the confounding bias and the endogeneity from the feedback effect owing to the plausible assumption that climate variables are exogenous and random. Similarly, all studies ranked 'very low bias' in terms of the stationarity threat because they were either cross sectional or short panel studies. In addition, most of the studies identified the possible problem of serial correlation and attempted to correct it using clustered standard errors at individual or regional level, hence all ranked 'very low bias' to 'low bias'. In terms of the reporting bias, all studies ranked below 'medium bias' as they all attempted to discuss their results from all angles. Therefore, the variations in the ranking of the studies emanated from the possibility of errors in the measurement of the dependent and independent variables, as well as in the extent to which the studies performed robustness checks to justify that their estimates are not spurious.

It is important to note that our assessment of bias was mainly centred on the causal interpretation of the temperature effects on education. As shown in table 2, nine out of 11 studies have more credible estimates, ranking below medium risk bias, while 2 were flagged to be interpreted with caution. The two studies (Pule *et al* 2021, Vu 2022) were flagged for having a relatively higher bias level, that is,

Table 2. Overview of the critical appraisal ratings of the internal validity of the reviewed studies.

First author	Year	Ranking (Bias)
Zhang	(2023)	Very low risk of bias
Arceo-Gomez	(2024)	Low risk of bias
Delprato	(2024)	Low risk of bias
Vu	(2022)	High risk of bias
Pule	(2021)	High risk of bias
Park	(2021)	Very low risk of bias
Li	(2021)	Low risk of bias
Zivin	(2020)	Very low risk of bias
Garg	(2020)	Very low risk of bias
Randell	(2019)	Low risk of bias
Randell	(2016)	Low risk of bias

Table 3. Effect of heat exposure on academic performance, school completion and school attendance.

First author, year	Negative effect on mathematics test	Negative effect on verbal, reading & language tests	Negative effect on score for combined subjects	Negative effect on school completion	Negative effect on school attendance
Arceo-Gomez (2024)	Yes	Yes	—	—	—
Zhang (2023)	Yes	No	—	—	—
Vu (2022)	Yes[a]		—	—	—
Garg (2020)	Yes	Yes	—	—	—
Zivin (2020)	—	—	Yes[a]	—	—
Park (2021)	—	—	Yes	—	—
Li (2021)	—	—	No	—	—
Delprato (2024)	—	—	—	Yes	—
Randell (2019)	—	—	—	Yes	—
Randell (2016)	—	—	—	Yes	No
Pule (2021)	—	—	—	—	Yes

[a] The small size of the effect was noted as an 'economically negligible' effect.

- No outcomes reported.

slightly above moderate. These concerns do not aggregate to the exclusion of the articles; the concerns indicate only that, considering their limitations, the articles should be interpreted with caution. We also acknowledge that these two higher bias assessments may be due to inadequate reporting of the methods used in the estimations, in the final published version of these papers.

3.9. Description of effects

The majority of the evidence on the effect of heat on educational outcomes came from studies reporting on academic performance as measured by test scores (7 out of 11 studies: (Garg *et al* 2020, Zivin *et al* 2020, Li and Patel 2021, Park *et al* 2021, Vu 2022, Zhang *et al* 2023, Arceo-Gomez and López-Feldman 2024). There was less evidence on the effect of heat on children's school completion (3 out of 11 studies: (Randell and Gray 2016, 2019, Delprato and Shephard 2024) and on school attendance (2 out of 11 studies: (Randell and Gray 2016, Pule *et al* 2021).

Table 3 provides an overview of the findings from each study, on the potential effects of heat on the three main areas of educational outcomes, namely academic performance, school completion and school attendance. Tables detailing quantitative effects reported in each study are presented in supplementary file 5(a)–(e). The supplementary tables include information on study author and date, outcome indicators, measurement indicators for heat, and outcomes and statistics for the reported effect's direction and size. Supplementary files 5(a)–(c) report on academic performance, supplementary file 5(d) reports on school completion and supplementary file 5(e) reports on school attendance.

Of the seven studies reporting on academic performance, the majority (six of the seven studies) reported evidence of negative effects of heat on mathematics, verbal and or combined test scores (Garg *et al* 2020, Park *et al* 2021, Vu 2022, Zhang *et al* 2023, Arceo-Gomez and López-Feldman 2024). Two studies reported little to no effect of heat on some test scores. These were Zhang *et al* (2023) on verbal scores, and Li and Patel (2021) on combined scores, the latter for university entrance examinations for students in Brazil. The three studies reporting on school completion all reported negative effects of heat

(Randell and Gray 2016, 2019, Delprato and Shephard 2024). One study reported negative effects on school attendance, finding that increased absenteeism with higher indoor classroom temperatures (Pule *et al* 2021).

While the majority of studies reported negative effects of heat on educational outcomes, the effect sizes were wide-ranging, and some studies reported no or negligible effects. From the reporting, it was not always clear how academically or economically meaningful these results were with respect to the loss of educational attainment. For instance, most studies only reported statistical effects, without giving a description of what this equates to in terms of educational loss in their setting.

3.10. Academic performance

As shown in table 3, seven studies reported test scores in three areas of academic performance, namely mathematics (4 studies), verbal, reading and language (or 'verbal') (3 studies), and combined school subjects (3 studies). Three out of the four studies reporting on mathematics scores also reported on verbal scores. Negative effects are reported for both mathematics and verbal scores, but more consistently for mathematics. The picture is mixed for test scores for combined school subjects. Details of the findings in and across these studies are reported below.

3.10.1. Mathematics test scores

Four studies reported a negative effect of heat on test score performance in mathematics, with one report noting that the small effect size was 'economically negligible' on an individual-student level (Vu 2022). For details, see supplementary file 5(a).

- According to household surveys in China, exposure to high mean temperatures above 32 °C on the day of low-stakes mathematics testing lowered the mathematics score by 0.066 standard deviations (SD), compared to cooler days (22 °C–24 °C). This was reported as being equivalent to nearly three months of lost education time (Zhang *et al* 2023). A sub-analysis found that the negative effect on the mathematics test scores was more salient for less educated individuals.

- For Vietnamese students taking university entrance examinations, an increase of 1 °F (0.56 °C) in temperature reduced the mathematics score by approximately 0.006 SD, which was reported as being a 1.64% loss in the raw testing score. The effect size was considered economically negligible on an individual-student level, but the authors noted that it may be economically significant at the national level, given Vietnam's large population size. A sub-analysis showed that the negative impact on women compared to men was larger, and statistically significant. No difference was found between people living in or not living in economically depressed areas (Vu 2022).
- Garg *et al* (2020) found that, for students in India, exposure to one day of high temperatures (of above 29 °C) in the previous year had a slight negative effect (0.003 SD) on mathematics performance in the year of testing.
- Arceo-Gomez and López-Feldman (2024) reported that a 1 °C increase in annual average temperature (compared to a reference range of 17 °C–21 °C) negatively affected low-stakes (regular) mathematics test scores amongst Mexican children, by 0.0331 SD. No interpretation of the impact of this effect size on educational loss was provided. Sub-analyses showed detrimental impacts are similar across urban and rural areas, across genders and across different levels of socio-economic marginalisation. In terms of historical climate, students in historically colder municipalities actually benefited from hotter temperatures.

3.10.2. Verbal test scores

Two out of three studies reported negative effects of heat on verbal, reading or language test scores, and one reported no effect (Garg *et al* 2020, Zhang *et al* 2023, Arceo-Gomez and López-Feldman 2024). For details, see supplementary file 5(b).

- Garg *et al* (2020) found a negative effect of heat on verbal test scores, for students in India, similar to that found for mathematics in the same sample population.
- Experiencing a year that is on average 1 °C hotter decreased the Spanish language test score by 0.07 SD (Arceo-Gomez and López-Feldman 2024).

- By contrast, Zhang *et al* (2023) found that (unlike the negative effects on mathematics scores for the same sample population) there was no obvious effect of heat on verbal test scores for students in China.

3.10.3. Combined subject test scores

Two of three studies reported negative effects of heat on combined test scores (combination of several school subjects), and one reported no effect (Zivin *et al* 2020, Li and Patel 2021, Park *et al* 2021). For details see supplementary file 5(c)

- Reporting on national examinations across 58 countries, Park *et al* (2021) found that the rate of learning decreased with an increase in the number of hot school days, and that this effect was more marked for poorer countries (Vietnam and Thailand). Each additional day above 26.7 °C (80° F) during the 3 years preceding an examination lowered scores by 0.18% of a SD. When reporting results disaggregated for poorer versus richer countries, Park and colleagues found a larger negative effect on poorer countries; the impact was significant in poorer countries ($\beta = -0.14$; $P = 0.001$; 95% CI $= -0.22$ to -0.07) but less so in richer ones ($\beta = -0.024$; $P = 0.733$; 95% CI $= -0.17$–0.12). No interpretation of the impact of this effect size on educational loss was provided.

- Heat reduced mathematics scores for Vietnamese students taking university entrance examinations (Vu 2022). Similarly, Zivin *et al* (2020) found a small negative effect on university entrance examination performance of Chinese students. A 1 °C increase in temperature from 2005 to 2011 decreased the total test score by 0.34% or 1.76 marks (at the mean level). While the overall size of the negative effect was small, the magnitude was larger with higher increases in temperature, and the effects were more concentrated in the higher performing students. A sub-analysis by subject track showed a larger negative effect of heat on the test scores in the art track (0.36%), whereas the reduction was smaller in the science track (0.18%).
- By contrast, Li and Patel (2021) reported that the effect of extreme heat (and other weather conditions like high humidity and rainfall) was negligible for performance on university entrance examinations for students in Brazil.

3.10.4. Complexity of cognitive tasks and student ability

One study made reference to the complexity of cognitive tasks, and one study referred to student ability as potential mediating factors.

- Garg *et al* (2020) reported that the negative effects of heat are greater when the questions are more complex/harder for both mathematics and reading tests.

- Zivin *et al* (2020) reported that test performance of high-ability students in China were more sensitive to temperature, with the lowest ability students being less affected. The authors noted this may imply a larger burden on the future career prospects of higher-ability students in China.

In sum, there was evidence of differential effects for academic performance in different school subjects, with more consistent negative effects for mathematics as compared to verbal scores and combined subject test scores.

3.11. School completion

Three studies reported on school completion, and all three reported on heat along with other weather conditions (precipitation, aridity, etc), so the results reported in these studies are not completely clear for the effect of heat alone (Randell and Gray 2016, 2019, Delprato and Shephard 2024). All three reported negative effects of heat and/or heat with other weather conditions. For details, see supplementary file 5(d).

- A child who experienced average spring temperatures 0.5 SD above the village's long-term mean in Ethiopia had a 21% lower odds of completing at least one grade of school (Randell and Gray 2016).

- A child in Southeast Asia who experienced early-life temperatures 2 SDs above average was predicted to attain 1.5 fewer years of schooling compared to one who experienced average temperatures (Randell and Gray 2019).

- Higher land-surface temperatures were associated with lower educational attainment across all educational levels (primary, middle and secondary) in Cameroon and Nigeria (Delprato and Shephard 2024). Aridity (a combined measure of heat and rainfall) was consistently associated with lower school completion rates across Guinea, Cameroon, Ethiopia and Nigeria, particularly in rural communities. This was seen to be linked to agriculture production, health, internal migration, food security and income (Delprato and Shephard 2024).

3.12. School attendance

One study reported negative effects of heat on school attendance, while another did not find an effect of heat. For details, see supplementary file 5(e).

- Pule *et al* (2021) found that absenteeism in rural South African primary school children increased at higher indoor temperatures (above 25 °C). Absenteeism was highest during periods with the lowest temperatures (below 15 °C). Classroom temperatures were affected by building characteristics such as the type of building material used for floors, ceiling and walls (e.g. prefabricated or brick walls).
- Randell and Gray (2016) did not find an overall effect of heat only, or of heat and rainfall combined. They found that children in Ethiopia who experienced average early life summer rainfall 0.5 SD above the village long-term average had 45% higher odds of attending school ($p = 0.011$).

3.13. Factors shaping the potential effect of heat exposure on educational outcomes

Several associated mediating variables were reported as influencing the effect of heat on education outcomes. Sub-analyses of these studies reported on: gender; educational level and socioeconomics; school building characteristics and air-conditioning; urban-rural continuum and historical climate; and heat combined with other weather conditions.

3.13.1. Effect of gender

Six out of the 11 studies commented on gender differences, with mixed results. Four pointed to some gender effect, noting a trend towards females being more heavily affected (Zivin *et al* 2020, Li and Patel 2021, Vu 2022, Delprato and Shephard 2024). Two studies reported that they found either little or no substantial differentiated effects between genders (Randell and Gray 2016, Arceo-Gomez and López-Feldman 2024).

- Vu (2022) found a small effect of heat on performance in high-stakes university entrance examinations in Vietnam. The authors noted that the negative impact on women compared to men was larger and statistically significant.
- Zivin *et al* (2020) reported a gender-related greater negative effect of heat on test scores in the arts track (history and geography), compared to the effect in the science track. The authors suggested that the heavier presence of females in the arts track may be the reason for this difference (Zivin *et al* 2020).
- Delprato and Shephard (2024) examined the effect of women's empowerment (as measured by low vs high levels of child marriage and fertility rates), and noted that, in Cameroon, gaps in women's empowerment saw a larger negative effect of heat on school completion. The authors recommended that women's empowerment be encouraged through education and socio-economic support.
- Li and Patel (2021) observed a large negative effect of heat, particularly for females' language test scores. They also reported positive impacts of heat on natural science test scores for both males and females.
- By contrast, Arceo-Gomez and López-Feldman (2024) found no gender difference in the size of the reported negative effects of heat on mathematics and Spanish test scores in Mexico.
- Randell and Gray (2016) found that the effects of climate on completing any schooling does not differ by sex for rural children in Ethiopia.

3.13.2. Effect of educational level and socio-economic factors

Eight of the 11 studies commented on the role of educational level (2 studies) and/or socio-economic factors (6 studies), with mixed results.

- In China, there was a larger negative effect on mathematic test scores for people who had less education, particularly if they achieved less than a high school education (Zhang *et al* 2023). By contrast, the effect of early heat exposure on long-term education in the global tropics was more pronounced for children from households with a higher education level of the head of the household (at least a secondary education), compared to households' heads with no education. This effect was more prominent in the two hottest regions (Randell and Gray 2019).
- With respect to socio-economic factors, three studies found no difference between richer and poorer areas in high-stakes examinations in Vietnam (Vu 2022) or China (Zivin *et al* 2020) or in regular examinations in Mexico (Arceo-Gomez and López-Feldman 2024).
- By contrast, Garg *et al* (2020), Arceo-Gomez and López-Feldman (2024) and Delprato and Shephard (2024) suggested that agricultural income may be the main mechanism for how high temperatures reduce performance in mathematics and reading scores. Garg *et al* (2020) suggested that providing a safety net for the poor via social protection grants weakened the link between temperature and test scores. The authors suggested that the absence of such social protection will probably have a higher negative impact on poorer agrarian economies.
- Of interest is that Park *et al* (2021) found that the worse test performance in poorer countries compared to richer countries was independent of changes in agricultural productivity. The authors suggested that cognitive stress from heat may be the key mechanism for poor academic performance (Park *et al* 2021).

3.13.3. School building characteristics and air-conditioning

Only two studies reported on the effect of building characteristics or air conditioning.

- In a rural South African setting, the relationship between indoor classroom temperatures and absenteeism was influenced by building characteristics such as the type of building material used for the floor, ceiling and walls (e.g. prefabricated or brick walls) (Pule *et al* 2021).
- Only one study reported on the effects of air conditioning, based on modelling data. Assuming urban areas would have greater access to air conditioners, Zivin *et al* (2020) modelled the difference between urban and rural areas in the effect of air conditioning on scores in university entrance examinations. They reported little difference in the impact of air conditioning. Zivin and colleagues noted that, in China, air conditioning during university entrance examinations is banned, reportedly for consistency across venues and noise reduction. They noted that it remains an open question whether air conditioning could mitigate heat effects in, for instance, urban heat islands.

3.13.4. Effect of urban-rural continuum and historical climate

Five studies reported mixed findings on whether the effect of heat differed between urban and rural settings (Randell and Gray 2019, Garg *et al* 2020, Vu 2022, Arceo-Gomez and López-Feldman 2024, Delprato and Shephard 2024).

- Rural students writing university entrance examinations in Vietnam were found to be more vulnerable to heat (Vu 2022). Rural communities were more affected by a combination of heat and rainfall in Nigeria and Cameroon. Delprato and Shephard (2024) suggested that this was probably linked to rural communities being more vulnerable to risks associated with agriculture production, health, internal migration, food insecurity and income.
- By contrast, Arceo-Gomez and López-Feldman (2024) found no difference in the effect of heat across urban and rural areas for mathematics scores of Mexican students.
- Urban households (and those with higher household education) were more vulnerable to education loss from early-life effects of heat in some tropical regions. Randell and Gray (2019) noted that this may reflect a differential vulnerability in urban areas, due to higher food prices, infectious diseases, and/or urban heat.
- Studies did not report differences in the effect of heat between cooler and hotter countries or between in-country regions with different historical climates

3.13.5. Effect of heat with other weather conditions

Although the effect of heat in combination with other weather conditions was not the focus of this review, we highlight for interest some of the reported mixed results.

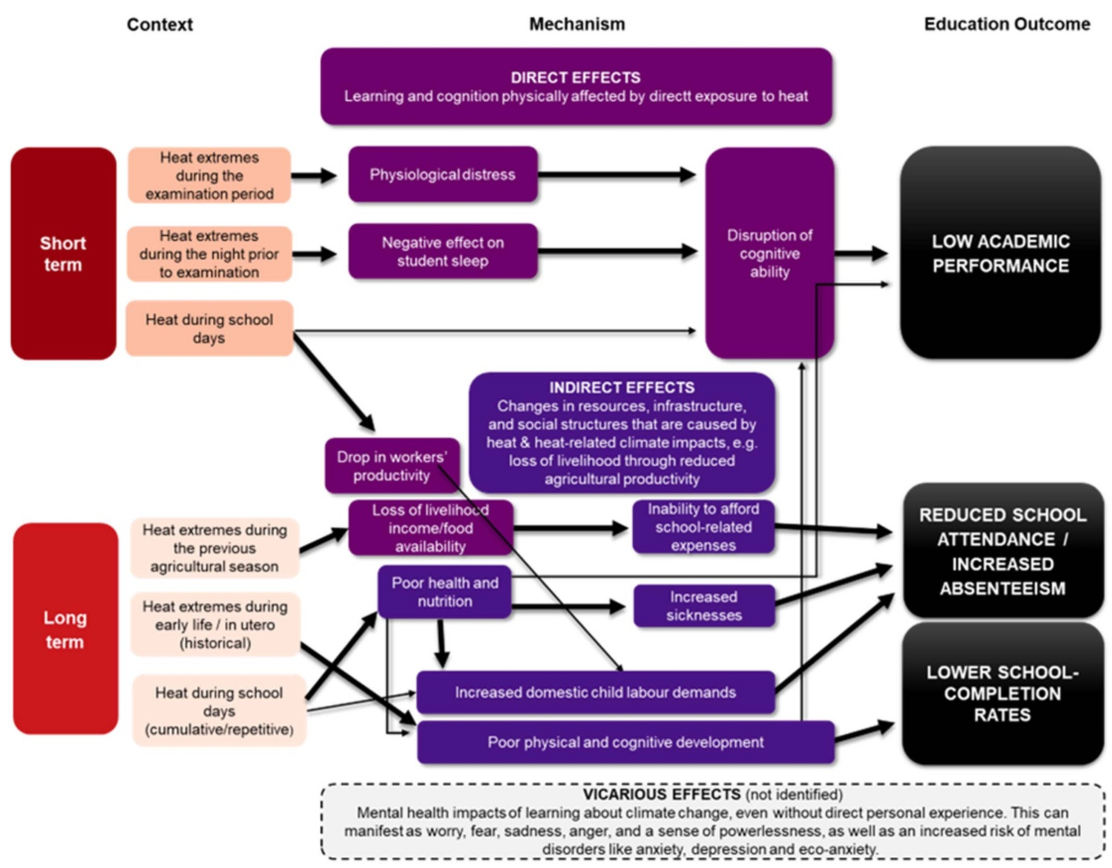

Figure 3. Illustration of emerging pathways through which extreme heat potentially affects the educational outcomes of children in LMICs.

- Zivin *et al* (2020) found little to no influence of precipitation, humidity, and pressure, but found a significant positive effect of wind speed and the longer duration of sunshine. The authors suggested that higher wind speeds may reduce perceived temperature (the 'wind chill' effect), and experiencing longer sunshine may induce a good mood and happiness.
- Children who experienced average early life summer rainfall 0.5 SD above the village long-term average in Ethiopia had 45% higher odds of attending school, which suggests that rainfall during the growing season is an important predictor of future schooling outcomes (Randell and Gray 2016). Similarly, exposure to early-life rainfall was positively associated with educational achievement in some regions (West and Central Africa), while negatively associated with educational achievement in others (Central America and the Caribbean) (Randell and Gray 2019).
- Delprato and Shephard (2024) found that aridity was consistently associated with lower school-completion rates, particularly in rural communities, and the authors noted that this suggests a link to agricultural production and food insecurity.

3.14. Emerging causal pathways for the potential effect of extreme heat on educational outcomes

The possible pathways for the effect of heat on educational outcomes in the included studies are illustrated diagrammatically in figure 3. The figure organises the findings into contextual exposure, mechanism and outcomes, to illustrate the different factors and components. Thick black arrows show the direction of the relationship as tested and described in the included studies. The mechanisms are categorised into resulting from short- and long-term exposure, and into direct and indirect mechanisms. Short- and long-term contextual factors differentiate the length of time between the exposure to heat and the measurement of educational outcomes. The short-term mechanism demonstrates the effect of school children's exposure to heat during school days, examination periods, or a night before the day of the examination.

As illustrated in figure 3, short-term pathways indicate that there are acute effects of heat on cognitive ability, either through physiological distress on the test day, affecting cognitive ability (Vu 2022, Delprato and Shephard 2024), or due to disrupted sleep the day before the test was taken (Zivin *et al*

2020). Long-term mechanisms refer to distal exposure of children to extreme heat, for example, during the previous agricultural season (Randell and Gray 2016, Garg *et al* 2020), in early life or in utero (Randell and Gray 2019, Delprato and Shephard 2024), or during school days in the past 1–3 years (Park *et al* 2021), and from cumulative or repetitive exposure (Zhang *et al* 2023).

Studies on short-term pathways reported a potential link between exposure to heat extremes during examination periods and poor academic performance through physiological distress and disruption of cognitive ability caused by heat stress (Delprato and Shephard 2024). This link was observed particularly for mathematics test scores. Zivin *et al* (2020) suggested that mathematical problem solving depends on brain function in an area of the prefrontal cortex and neural circuits that are sensitive to heat.

Li and Patel (2021) noted that temperature can play an important role in high-stakes cognitive performance for students aiming to enter university, and this was noted as having potentially far-reaching impacts for the career development and lifetime earnings of students. Li and Patel reflected on the potential reasons as they found little to no effect of heat on exit examination scores for Brazilian students. They highlighted the high-stakes context of the test. Li and Patel stated that, in Brazil, the high level of student preparedness may be the reason why shifts in weather conditions on the test day did not have a negative effect, as students prepare for the university entrance examinations for several months or years. They also noted that students may be adjusting to increases in heat and may therefore be less susceptible on the day of testing. It is unclear why results for Brazil (Li and Patel 2021) and Vietnam (Vu 2022) (finding little to no negative effect) differed from the negative effect of heat reported for high-stakes examinations for Chinese students shown by Zivin *et al* (2020).

Long-term, indirect pathways were suggested that potentially both reduce school attendance and lower school completion rates. Randell and Gray (2016) suggested that this indirect effect may be through loss of livelihood emanating from reduced agricultural productivity. Heat extremes during the previous agricultural season may have contributed to the loss of livelihood income and subsequent reductions in food availability, thereby leading to poor health and nutrition (Randell and Gray 2016). Loss of livelihood may also lead to the inability of families to afford school-related expenses, which may lead to increased school absenteeism (Delprato and Shephard 2024). Garg *et al* (2020) makes the case that, for low-stakes tests in India, agricultural income may be the main mechanism for how heat may reduce performance in mathematics and reading scores. These authors noted that providing a safety net for the poor via social protection grants weakens the link between temperature and test scores, and that the absence of such social protection may have a higher negative impact on poorer agrarian economies compared to urban economies. Long-term pathways point to a potential link between early life exposure (heat in-utero and during early infancy) and poor academic performance, which is possibly mediated through poor health and nutrition (Randell and Gray 2019). Randell and Gray (2019) noted that, in some settings, families with a higher educational level may be more negatively affected and may be at greater risk of losing the educational gains they made. These authors argued for policies that reduce early childhood vulnerability to heat, including policies regarding food security, income stability and limiting heat exposure (Randell and Gray 2019).

4. Discussion

4.1. Summary of findings

This review could not provide a pooled estimate of the effect of heat extremes on educational outcomes. The review highlighted the diversity of studies in terms of methods, heat exposure and educational outcome measures. Some studies focused on heat only, while others combined heat with other weather conditions such as precipitation, humidity or aridity. Spatial coverage varied (e.g. across global regions, across multiple countries, country-wide, and including within-country sub-analyses) as did the timing and duration of heat exposure in relation to when outcomes were measured (e.g. the day of or the day before examinations, months or years prior to examinations, early childhood exposure). Most of the studies drew on global and regional weather surveillance data sets. The studies used varied statistical models to measure the effects of heat and used various statistical measures for heat (e.g. mean, average, cumulative, temperature ranges or bins). Generally, it was not possible to tell which heat measures may be more effective in measuring effects, although one study (Zivin *et al* 2020) noted that contemporaneous temperatures (especially maximum daily temperature) and the temperature just before the examination provided a more statistically significant effect of heat.

Educational outcomes varied and included academic performance, school attendance and school completion, with some variation in how these were measured. Academic performance included regular and high-stakes examinations, the latter being university entrance examinations that impacted students' career development directly. The target population included primary and/or secondary school learners, and youth completing cognitive tests at home as part of a nationwide household survey. Studies mostly drew on national or comparable regional data sets on standardised academic tests. There was more evidence (based on a number of studies) on academic performance (national-level mathematics, verbal and combined subject tests) and less evidence on school completion and school attendance.

More studies reported negative effects from heat, but some showed little to no effect (especially for university entrance examinations). This trend towards more studies reporting negative effects is in line with findings from other review reports that also highlighted negative effects (Pankhurst 2022, Leal Filho *et al* 2023, Marin *et al* 2024). This review highlights the complex relationship between various contextual and mediating factors such as subject type (e.g. mathematics or other), complexity of cognitive tasks, student ability, household educational level, gender, socio-economic factors including food security and financial safety nets, urban-rural continuum, school building characteristics, historical climate and the combined effect of heat with other weather anomalies.

With respect to mechanisms through which heat extremes potentially affect children's educational outcomes, this review points to two of the three main causal pathways proposed in the literature. Reviewed studies pointed to cognitive distress (through physiological distress and cognitive decline) being a potential direct causal pathway for acute and cumulative effects on learning ability and academic performance on the day of and/or the day before testing. This is in line with the literature on physiological responses to elevated classroom temperatures, which include an increased heart rate and an altered perception and spatial orientation (Brink *et al* 2021). These physiological effects can reduce accuracy and speed in cognitive tests and thus translate into diminished learning outcomes (Porras-Salazar *et al* 2018, Barbic *et al* 2019, 2022, Wargocki *et al* 2019, Tian *et al* 2021, Vu 2022). For instance, a systematic review on ambient air temperature and cognitive performance found that hot temperatures led to a 5% decrease in accuracy and a 3% decrease in speed in cognitive tasks (Yeganeh *et al* 2018). Practical suggestions for schools in heat-prone areas include adjusting academic calendars, such as shifting national examination dates to cooler months or class time to cooler parts of the day (Yeganeh *et al* 2018, Garg *et al* 2020, Shortridge *et al* 2022).

Medium-term heat exposure and heat anomalies (exposure 1–3 years prior to test taking) could potentially affect academic performance. The suggested pathway is through accumulated loss of learning time, as described in the literature. For instance, studies showed that, for every additional day of extreme heat, at least one day of learning is lost (Cho 2017, Garg *et al* 2020, Park *et al* 2020, 2021, Roach and Whitney 2022). Another medium- to long-term pathway highlighted in this review involves indirect distal effects associated with the loss of livelihood arising from reduced agricultural productivity. There is evidence that economic stressors may not only diminish households' capacity to afford education but also involve absenteeism from school due to children helping with food production (Lassa *et al* 2023). Poorer agrarian communities may be particularly vulnerable. The potential risks of early-life exposure to heat and the increased risks for poorer agrarian communities, noted in this review, are also echoed in the literature. For instance, studies have argued for policies that reduce vulnerability to extreme temperatures, particularly during early childhood, by ensuring food security and income stability, and by limiting heat (United Nations Children's Fund [UNICEF] 2021a, Kroeger 2023).

We did not find evidence on heat impacting school closures, road closures and/or other disruptions of school infrastructure (e.g. internet access), or evidence on heat affecting teacher absenteeism or teacher performance. We also did not find evidence on vicarious effects such as heightened anxiety about climate change, despite emerging evidence of this (Léger-Goodes *et al* 2022).

4.2. Implications for research

The evidence base is relatively new, with most of the reviewed studies published in the past six years. The relatively small number of studies found points to the thinness of the evidence base. More standardised study designs, exposure measures and outcome measures, with statistically comparable data, are needed to enable pooled estimates and to strengthen evidence.

There were fewer studies from vulnerable regions like sub-Saharan Africa and Southeast Asia. This gap highlights the need for more research in underrepresented regions to capture diverse climatic (including regional differences), socioeconomic and educational settings, to promote a more comprehensive understanding of heat's impact on learning. Furthermore, most of the reviewed studies focused on high school students, particularly those writing university entrance examinations, which points to a gap in the study of primary schooling.

Three types of educational outcomes were examined: academic performance, school attendance, and school completion. Compared to academic performance, there was less focus on school attendance and completion, and none of the studies explored school enrolment and school dropout rates, which are crucial for understanding long-term impacts. More consistency in reporting outcome measures would allow for more meaningful comparisons.

Except for one study on school building material and one on air-conditioning, we did not find studies on the effect of extreme heat on school infrastructure. We did not find evidence on the educational effects of heat-related school closures, road closures or other disruptions to school infrastructure and functioning (e.g. internet access, teacher absenteeism or reduced teacher performance). We also did not find evidence on vicarious effects such as heightened anxiety about climate change, despite the emerging evidence of this (Léger-Goodes *et al* 2022). These gaps could be topics for further study. Finally, a more holistic study approach may be needed to assess the evidence on the effects of heat on education and theoretically inform the potential pathways of these effects. Such studies may benefit from considering associated social-welfare and health outcomes.

4.3. Implications for policy and practice

There is increasing recognition of the intersectional relationship between inequality and the impact of climate change (Tschakert *et al* 2025, Zamir *et al* 2026). This includes the 'triple threat' of climate vulnerability, income inequality and gender parity on educational access and outcomes (Tschakert *et al* 2025). Resilient education systems are crucial for mitigating climate-change risks, by acting as both a defences against disruptions and a driver for sustainable adaptation. Resilient education can include green, durable infrastructure and climate-focused curricula and education systems that protect learning, reduce future damage costs and empower educational systems and students to act on climate solutions. Yet we know little about effective and feasible adaptation options that will reduce the effects of extreme heat on education outcomes in LMICs (Marin *et al* 2024). Given the multiple pathways linking heat stress to educational outcomes, adaptation will be required along multiple dimensions. Some of the studies reviewed here point to potential recommendations.

Studies have called for increased community resilience, through enhancing infrastructure, providing access to educational resources and integrating climate adaptation strategies with education. Investments in school infrastructure were recommended. For instance, several reviewed studies highlighted the need for policies to improve the physical learning environment, to reduce acute physiological effects of heat (Garg *et al* 2020, Park *et al* 2021, Pule *et al* 2021, Vu 2022, Delprato and Shephard 2024). School planning and design should consider the climate-proofing of classrooms to ensure thermal comfort (Garg *et al* 2020, Park *et al* 2021, Pule *et al* 2021, Vu 2022). This includes using better design, materials, orientation, ceilings and cooling mechanisms, reducing crowding and integrating shading or greening solutions to climate-proof classrooms. Some of the reviewed articles mentioned air conditioning as a possible intervention to improve student cognition and teacher retention (Garg *et al* 2020, Zivin *et al* 2020, Park *et al* 2021), although the broader climate impact of providing air conditioning would need to be considered carefully. Practical recommendations included the adjustment of academic calendars, such as by shifting school-leaving examination dates to cooler months to reduce heat-related declines in performance. Moreover, schools in heat-prone areas could adapt by adjusting school hours to start earlier or by shifting to evening classes and exploring hybrid learning models during extreme heatwaves (Garg *et al* 2020, Park *et al* 2021).

Several studies emphasised the need for policies that reduce people's economic vulnerability to extreme temperatures, particularly during early childhood, by ensuring food security and income stability, and by limiting heat exposure, particularly for the economically vulnerable (Randell and Gray 2016, 2019, Garg *et al* 2020, Delprato and Shephard 2024). The studies highlighted the importance of providing social protection programs to mitigate disproportionate adverse effects of heat in poorer agrarian communities (Randell and Gray 2016, 2019, Garg *et al* 2020), as well as the need to shift to more heat-resistant crops (Garg *et al* 2020). Studies emphasised the need to address gender disparities and barriers to education, including by encouraging women's empowerment (Randell and Gray 2016, Park *et al* 2021, Delprato and Shephard 2024). Examples from beyond this sample highlight promising nature-based adaptation interventions for schools, including the provision of improved vegetation, fountains and shade structures that can decrease heat and improve school environments (Sanz-Mas *et al* 2024). These interventions have also demonstrated co-benefits for broader education and development goals, such as play opportunities, reduced conflict and social inclusion (Sanz-Mas *et al* 2024).

In sum, policies for a safe and resilient physical learning environment and for strengthening economic resilience in climate-affected communities, particularly in rural, agriculture-dependent areas, are key.

4.4. Strengths and limitations of the review

The registration of the study protocol is a strength of this study as the protocol guides the review methods in a more transparent way than an unregistered protocol would. Extreme heat studies are challenging to identify, given that climate-change studies are spread across different disciplinary areas using a variety of index terms that makes climate change harder to track. To increase the comprehensiveness of our search, we strengthened our systematic search strategy approach with supplementary search strategies.

Nevertheless, our search could have missed eligible studies. Potentially relevant evidence in grey and non-English literature would have been missed, thus limiting the comprehensiveness of this review. We excluded studies that combined heat and other weather conditions, where the effect of heat was not reported separately, which further narrowed the scope. We also did not specifically search for vicarious effects of heat. Finally, given the small number and the diversity of the studies that we found, including qualitative studies would have added valuable context, but this fell outside the scope of our review.

Some studies did not provide sufficient details in reporting their work. This limited the quality and usefulness of the findings we could synthesise for this review. For instance, there were gaps in the details of study designs and conflicts of interest, and in the meaningful interpretation of the statistical findings. The critical appraisals we conducted helped to offset some concerns about the studies' quality. Although these critical appraisals were not formally used to inform levels of confidence in our review findings, the appraisals did provide a useful overview of the quality of the underlying evidence that informed our findings. We described the findings from a small number of studies in detail, and we caution against the risk of overgeneralisation given the small evidence base of only11 studies.

5. Conclusion

There is evidence of potential negative effects of heat on academic performance, although the ranges in the effect size and mediating factors highlight the complexity of the relationship between extreme heat and educational outcomes.

Findings from these studies should be viewed in context, and one-size-fits-all policy recommendations may not be appropriate to all settings. Policy makers and managers ought to consider policies holistically at institutional and systemic levels, across education and other sectors, to prevent and mitigate the negative impact of heat on educational achievement. Policies regarding climate-resilient education infrastructure and learning systems may be needed to mitigate the effects of particularly acute heat on the cognitive functions of learners. Policies may also be needed to attenuate the economic vulnerability associated with heat-related risks to livelihood, particularly in poorer agrarian communities; economic safety nets may be a necessary inclusion in such policies.

More studies are needed to expand the evidence base regarding the effect of heat extremes on education outcomes. More comparable evidence of effect, including health and social-welfare impacts, the interaction of heat with other weather conditions and regional weather variations, could usefully inform further policy recommendations.

Acknowledgments

This research was supported through funding from Schmidt Sciences (CHT, NPS), AXA Research Fund (CHT), and the UKRI GCRF Accelerating Achievement for Africa's Adolescents (Accelerate) Hub (ES/S008101/1). This work does not reflect the views of the funders nor the institutions where the authors are based.

We also acknowledge our information specialist librarians (Ms Tamzyn Suliaman and Ms Jamie Hendricks) at the UCT Social Sciences library who assisted with refining the search strategy, and with conducting the pilot searches. We acknowledge Dr Jane Kelly who assisted with peer-reviewing this review.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Academic database search terms: Supplementary file 1 available at https://doi.org/10.1088/2515-7620/ae6037/data1.

Data extraction template: Supplementary data file 2 available at https://doi.org/10.1088/2515-7620/ae6037/data2.

Critical Appraisal Assessment: Supplementary file 3 available at https://doi.org/10.1088/2515-7620/ae6037/data3.

Critical Appraisal Approach: Supplementary file 4 available at https://doi.org/10.1088/2515-7620/ae6037/data4.

Tables summarizing effects: Supplementary files 5(a)–5(e) available at https://doi.org/10.1088/2515-7620/ae6037/data5.

Ethics

A systematic review of published literature does not require institutional ethics approval within our institutions.

Conflict of interest

The authors are funded through academic institutional funds and do not have any financial or non-financial competing interest.

Funding

This research was supported through funding from Schmidt Sciences and the UKRI GCRF Accelerating Achievement for Africa's Adolescents (Accelerate) Hub (ES/S008101/1). This work does not reflect the views of the funders nor the institutions where the authors are based.

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