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Review article

Effects on child and adolescent health of climate change mitigation policies: A systematic review of modelling studies

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ABSTRACT

There is a growing body of modelling evidence that demonstrates the potential for immediate and substantial benefits to adult health from greenhouse gas mitigation actions, but the effects on the health of younger age groups is largely unknown. We conducted a systematic review to identify the available published evidence of the modelled effects on child and adolescent health (≤18 years of age) of greenhouse gas mitigation. We searched six databases of peer-reviewed studies published between January 1, 1990 and July 27, 2022, screened 27,282 original papers and included 23 eligible papers. All included studies were set in high- and middle-income countries; and all studies modelled the effects of interventions that could mitigate greenhouse gas emissions and improve air quality. Most of the available evidence suggests positive benefits for child and adolescent respiratory health from greenhouse gas mitigation actions that simultaneously reduce air pollution (specifically PM2.5 and nitrogen dioxide). We found scant evidence on child and adolescent health from regions more vulnerable to climate change, or on mitigation interventions that could affect exposures other than air pollution.

1. Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) reported that global surface average temperature is estimated to increase by 1.6°–2.4 °C (range 1.2–3.0 °C) by mid-century (IPCC et al., 2021). Fossil fuel combustion is a major source of the greenhouse gases (GHG) driving climate change (IPCC et al., 2021) leading to negative impacts on health worldwide including increased mortality, undernutrition, adverse effects on mental health, and increases in vector- and water-borne infectious diseases (Lieber et al., 2020; Phalkey et al., 2015; Stanke et al., 2013; Sharpe and Davison, 2021; Perera and Nadeau, 2022).

There is a growing body of evidence on the potential effects on adult health of policies designed to mitigate climate change, i.e. reduce greenhouse gas emissions (Bikomeye et al., 2021; Remais et al., 2014; Springmann et al., 2017; Shindell et al., 2021). To-date there is little known about the effects on child and adolescent health of such policies even though children are known to be more vulnerable to some forms of climate change-related hazards due to both their physiology and their social/developmental needs (Ahdoot et al., 2015; Seal and Vasudevan, 2011; Sheffield and Landrigan, 2011; Xu et al., 2012; Perera and Nadeau, 2022; Leffers, 2022). Moreover, children are a particular at-risk group in that more than 99% of children worldwide have been exposed to at least one hazardous consequence of climate change (UNICEF, 2021). The available evidence in adults suggests that climate change mitigation actions to reduce GHG emissions can have positive impacts on health (so-called "co-benefits") although they may also have adverse effects on health (IPCC et al., 2021; UNFCCC, 2021; Haines et al., 2009). These impacts are defined as "A positive effect that a policy or measure aimed at one objective has on another objective, thereby increasing the total benefit to society or the environment." (IPCC, 2022a). Impacts on adult health have been demonstrated from mitigation interventions in a variety of sectors including electricity production, transportation, agriculture and food, housing and industry (Gao et al., 2018; Chang et al.,

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2017; Gallagher and Holloway, 2020; Quam et al., 2017).

In addition to being more vulnerable, children are more exposed to pollutants due to their lower body weight compared to adults (Ahdoot et al., 2015; Perera and Nadeau, 2022). Thus, investing to protect children's health and future will have important benefits for the society. Children should be at the centre of policies for sustainable development and should be treated as equal stakeholders; a fact that is only recently receiving attention (Clark et al., 2020; Luthen et al., 2021; UNICEF, 2021). The United Nations Committee on the Rights of the Child has been developing recommendations aimed at protecting a healthy and sustainable environment for the benefit of children (General Comment No. *26*, 2023).

In this systematic review, we summarize the available published studies that focus specifically on policies or actions aimed to mitigate GHG emissions and model the potential impact of such mitigation on the health of children and young people ≤18 years. We also identify research priorities to inform environmental and health policies.

2. Methods

2.1. Search strategy

This review is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) updated guidelines (Page et al., 2021). The systematic review methods were published in advance of data collection on the PROSPERO register (protocol number CRD42021271717).

We performed a search of peer-reviewed literature to identify studies modelling the effects on health in children and young people ≤18 years of age of policy actions intended to (or likely to) mitigate climate change by reducing emissions of GHGs interventions (See Box 1 for examples).

We searched the following databases: OvidSP MEDLINE, OvidSP PubMed, OvidSP EMBASE, Global Health, Scopus, and ISI Web of Science for articles published between January 1, 1990 and July 27, 2022.

The search strategy was developed initially in MEDLINE with the same search terms used with minor adjustments as required for the input to other databases. The strategy included terms on direct GHGs and air pollutants, transportation means, dwellings, diets, combined with terms on climate change, mitigation, sustainability, and terms on general health impacts and co-benefits (with no restriction to any health outcomes). The search was restricted to children and adolescents. The full search strategies for each database are detailed in supplementary material (Table S1).

2.2. Selection criteria

We adapted the PICOS model to frame our selection criteria:

Participants: children and adolescents ≤18 years.

Intervention: any intervention intended or expected to reduce GHGs emissions.

Comparator: exposures under a counterfactual business as usual scenario or current exposure.

Outcome: any type of health outcome

Study design: modelling studies simulating the effect of climate change mitigation measures on health-related exposures and health effects.

Additionally, studies had to be published peer-reviewed papers in English.

Animal studies were excluded as were reviews and systematic reviews (the reference lists of which were searched for relevant studies). Epidemiological studies (e.g., observational studies and randomized control trials) were excluded if they contained no elements of evaluating modelled mitigation policies and forecasting future outcomes.

2.3. Selection process and data extraction

After removal of duplicates, records obtained through the search were divided among five reviewers (RP, ADD, JM, RJ, FK) who screened titles and abstracts for relevance. A random sample of 10% of the records for each reviewer was screened by a second reviewer from among the five reviewers. Papers selected for full-text review were read by two reviewers (RP, ADD). Consensus on any discrepancies was reached through discussion with a third reviewer (JM). Data were extracted by two reviewers (RP, RJ). Data included: type of health outcome, type of exposure, mitigation policy or intervention, population and study design, geographic area, temporal scale, health metrics (e.g., DALYs, number of cases, hospital visits), and comparator.

2.4. Risk of bias

The assessment of the risk of bias was carried out by two independent researchers (RP and RJ), and discrepancies resolved through consensus with a third researcher (JM). A checklist was generated by adapting the guidelines described in Hess et al. (2020) and Bennett and Manuel (2012). The checklist assessed whether the papers reported several elements, such as mitigation policies, study area, sources for population, emission and health data, scenarios, assumptions, concentration-response function, uncertainty and sensitivity analyses, and valuation. Each criterion of the checklist was scored as reported (score = 1); partially reported (score = 0.5); not reported (score = 0). The quality of each study was represented by the score percentage obtained by dividing the total score by the number of criteria evaluated in the assessment.

2.5. Data synthesis

Eligible papers were divided into two tiers. Tier 1 papers reported results specific to age categories ≤18 years old. Data from tier 1 studies were extracted as described in 2.3 above. The heterogeneity of models, methods, assumptions, policy and GHG reduction scenarios, and exposure-response coefficients did not allow for any meta-analyses to be performed. The main results of individual studies were reported in tables and summarized in narrative form. Tier 2 papers included children and

Box 1. Examples of policy actions searched for include, but are not limited to:

- Switching to low carbon energy and transport systems.
- Switching to cleaner forms of household energy.
- Policies to reduce trip distances and switching journeys to active forms of travel (walking, cycling).
- Policies that encourage the adoption of more sustainable dietary patterns which, in turn, would reduce emissions by changing agricultural practices.

adolescent populations, but the age categories did not allow separation of the population under 19 years from older individuals. Data extracted included: geographic area, mitigation policy or intervention, air pollutants, and health outcomes.

2.6. Role of the funding source

The funder did not play a role in the design and conduct of the study, collection, analysis, and interpretation of the data, preparation, review, or approval of the manuscript.

3. Results

3.1. Literature search

The initial search identified 35,881 studies with two additional records obtained through citation searches. After removing duplicates, 27,282 unique records were screened based on titles and abstracts, and 86 were included for full text review (Fig. 1). After full-text review, 18 studies were excluded because they included only populations older than 18 years of age, 40 were excluded because of their study design (e.g., did not include models evaluating climate change mitigation policies; reviews), and one was excluded because it was not in English. We could not retrieve the full text of three papers. In total, 23 records reporting models of the effects on child and adolescent health of GHG mitigation policies were eligible (Fig. 1). Of these eligible studies, 16 papers were included in tier 1 (specific to ≤18 years) level, and 7 papers were included in tier 2 (≤18 years and adults combined).

3.2. Geographical setting

Most Tier 1 studies modelled actions in the USA (n = 6), and Europe (n = 5); other settings included Asia (n = 4), Latin America (n = 1) and Australia (n = 1). No studies were set in Africa (Table 1). Tier 2 studies were set in high-income countries (n = 5) and upper-middle-income countries (n = 2) (Table S2).

3.3. Sectors

Scenarios explored the consequences of mitigations policies mainly in three sectors: energy, housing, and transportation (Table 1). Sectors were classified according to the definitions adopted in the Sixth Assessment Report of the IPCC (IPCC, 2022b). Five studies modelled scenarios where the reduction of particulate matter, i.e. PM2.5 and PM10, and ozone were the result of interventions in the energy sector (Abel et al., 2019; Kan et al., 2004; Perera et al., 2020; Thompson et al., 2016; Schucht et al., 2015). Two of these studies included scenarios evaluating the effects of a CO2 tax and cap-and-trade policy (Kan et al., 2004; Thompson et al., 2016). A study set in Europe modelled the effects of current and planned air quality legislations until 2030, with or without other restrictions to keep the average global temperature below 2 °C by 2100; their models entailed reductions of PM2.5 b y 75% with air quality legislations without Climate Change policies, and an additional 68% reduction with air quality legislation and policies to limit global temperature (Schucht et al., 2015).

Three studies focused on household air pollution, and the reduction of PM2.5 and PM10 through the use of more efficient and clean boilers (Adamkiewicz et al., 2021), reduction of the use of solid fuels (Staff Mestl et al., 2006) and the use of low emissions cook stoves (Wilkinson et al., 2009). Five studies simulated interventions on the transport sector. Four of them simulated the reduction of PM2.5 and NO2 through interventions on ground transportation such as limiting vehicle use, limiting speed, re-distributing traffic (by building a new section of highway), or promoting use of alternatives to cars (Host et al., 2020; Malmqvist et al., 2018; Schram-Bijkerk et al., 2009; Xia et al., 2015). One study simulated the use of a low emission technology at a rail yard

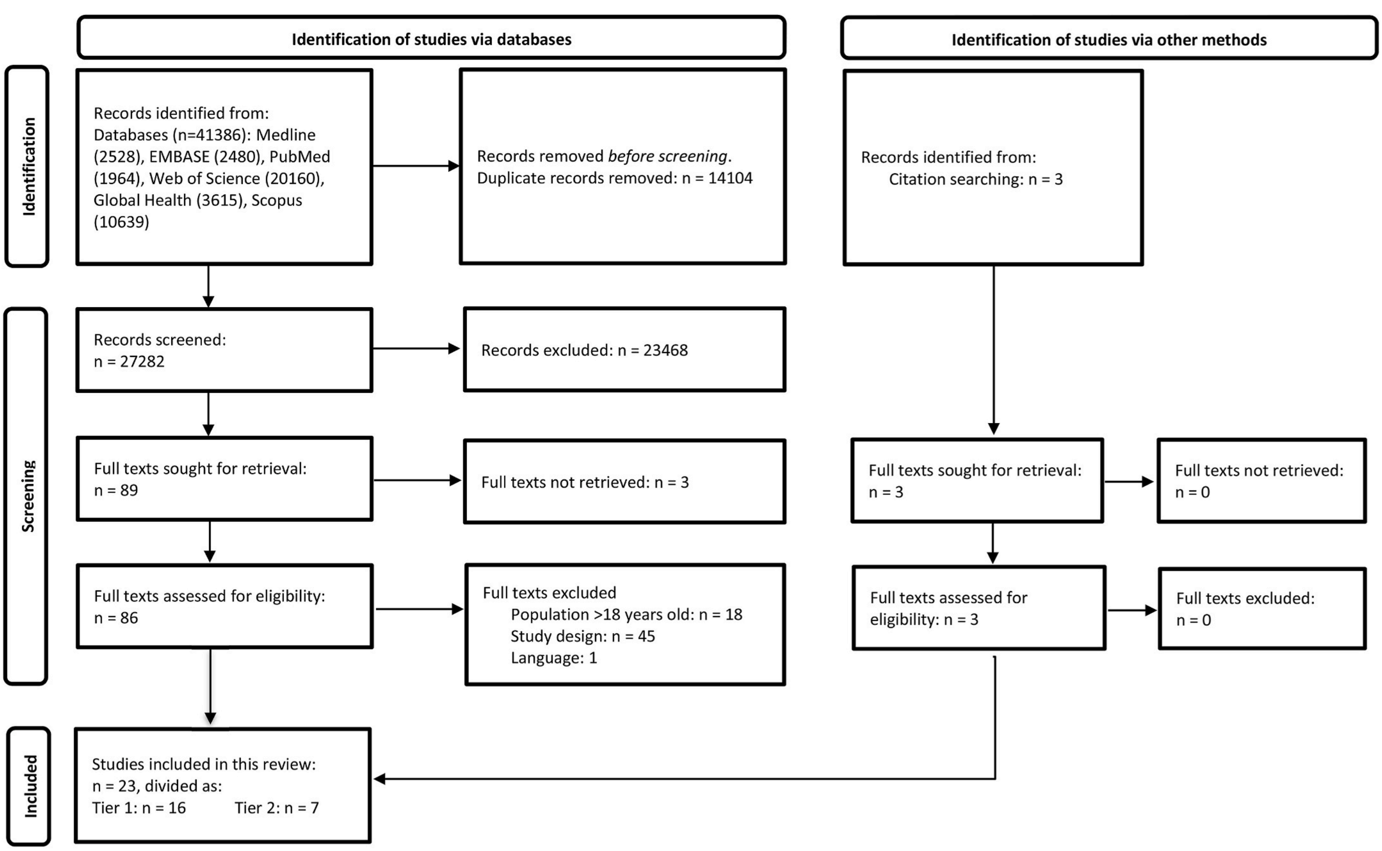

Fig. 1. Flow diagram of search. Modified from Page et al. (2021).

Table 1
Characteristics of tier 1 studies.

Sectors	Reference	Study location	Scenarios	Timeline	Pollutant: reduction
No specific sector/ multiple sectors	Cifuentes et al., 2001	Santiago (Chile), Mexico City (Mexico), Sao Paulo (Brasil), NYC (USA)	Reduction of GHG emissions over 20 years through the use of available technologies to mitigate GHG emissions in energy, transport, residential, and industrial sectors	BY:2000 Model: 2020	PM10, O3 10% reduction
	Hubbell et al., 2005	USA	Reduction of ozone to meet the US EPA daily 8-h standard	BY: 2000–2002	O3: reduce to ≤84 ppb any area that is above this limit
	Kuylenstierna et al., 2020	Bangladesh	NDC existing measures: 15% reduction energy use by 2021, 20% reduction by 2030.10% electricity from renewables in 2020.100% brick kilns converted to zigzag kilns by 2030.1.5 million improved cookstoves in 2015 NDC additional measures: 100% new coal-based plants use new more efficient technology.15% improvement in fuel efficiency by 2030. Increase wind and solar capacity. NDC possible measures: All biomass stoves replaced by improved ones or LPG by 2030.25% reduction energy intensity by 2030. Alternate wetting and drying of rice paddies (20%). 70% landfill gas captured by 2030.50% organic waste diverted from landfill to composting. SLCP action: 100% of rice parboiling units converted to efficient units by 2040. No crop residue burned in fields by 2040.100% of vehicles meet Euro IV standard by 2030. Type II and Type II Passenger cars running on motor gasoline converted to CNG by 2040.17% Reduction of CH4 emissions from livestock by 2040.100% domestic wastewater in urban areas treated through aerobic treatment plant, and 100% of domestic wastewater in rural areas through septic tanks by 2040.100% reduction in emissions from natural gas distribution and processing by 2040	BY: 2010 Model: 2030	PM2.5 (kilotonnes) in 2030 Baseline: 1157 NDC existing: 79 (−10%) NDC additional: 0 (0%) NDC possible: 225 (−30%) SLCP action: 41 (−5%) All measures: 345 (−45%)
Energy	Abel et al., 2019	Continental USA	Scenario 1 = current power system. No energy efficiency. Scenario 2 = energy savings of 348 TWh annually (or 91 TWh decrease in generation over the summertime). 15% reduction of electricity.	BY: 2016	Summer (3 month) average: O3: 66.56 ppbv (29.47–125.29) PM2.5: 3.11 μg/m^3 (0.787–38.08) Reduction from baseline: O3: 0.313 (0.45%) PM2.5: 0.022 (0.55%)
	Kan et al., 2004	Shanghai (China)	Scenarios to reduce PM10 through energy efficiency, gas replacing coal, CO2 tax	BY: 2000 Model: 2010, 2020	PM10 (μg/m^3) 2000 2010 2020 Base case: 27.66 39 54.1 Energy efficiency: 37 48 Gas: 30 35 CO2 tax: 22 21
	Perera et al., 2020	North-East of the USA	Evaluation of the US Regional Greenhouse Initiative	Evaluation from 2009 to 2014	PM2.5: reduction shown at county level in a map
	Schucht (2015)	Europe	Impact of climate policies on air quality. Reference: All current and planned air quality legislations until 2030. No policies for Climate Change Mitigation: All current and planned air quality legislations until 2030. Limit on global temperature change to 2 °C in 2100.	BY: 2005 Models: 2050	PM2.5 (μg/m^3), annual population weighted average Baseline 6200 per million inhabitants Reference 1500 (−75%) Mitigation 500 (additional −68%)
	Thompson et al., 2016	USA	Analysis of two subnational carbon policies Scenario 1: CES, clean energy standard Scenario 2: CAT, cap-and-trade	BY: 2006 Model: 2012–2030	PM2.5, O3: reduction shown in a map
Household	Adamkiewicz et al., 2021	Poland (two provinces)	Scenario 1: replacement of all poor-quality coal-fired boilers with gas boilers Scenario 2: replacement of all poor-quality coal-fired boilers with low-emission boilers but still using solid fuels Scenario 3: thermal refurbishment of houses with the worst insulation.	BY:2015	PM10 (μg/m^3), annual population weighted concentration Lower Silesia Baseline: 33.5 μg/m^3 Sc.1: 10.2; Sc.2: 7.82; Sc.3: 5.01 μg/m^3 Lodzkie province Baseline: 42.5 μg/m^3 Sc.1: 12.8; Sc.2: 10.6; Sc.3: 9.12 μg/m^3
	Staff Mestl et al., 2006	Shanxi province (China)	Reduction household solid fuels (mostly coal) for cooking and heating	BY: 2000	PM10 (μg/m^3) Background. Winter: 140; Summer: 80

(*continued on next page*)

Table 1 (*continued*)

Sectors	Reference	Study location	Scenarios	Timeline	Pollutant: reduction
					After intervention: Urban: reduce PM10 by 9700 tonnes/yr Rural: reach background levels
	Wilkinson et al., 2009	India	Introduction of low-emissions household cookstoves	BY: 2010 Model: 2020	PM2.5 ($\mu g/m^3$) 24-h personal exposures: 200-500 Reduction to 35
Transportation	Galvis et al., 2015	Atlanta (GA, USA)	Adopting low emissions technology at a rail yard	BY: 2011	PM2.5 (3% and 5%)
	Host et al., 2020	Greater Paris (France)	Four low emission zones scenarios involving traffic restrictions	BY: 2018–2019	NO2 in Paris 1. BAU: 28–55 $\mu g/m^3$ Reduction: 20–42 $\mu g/m^3$ 1. BAU: 29–58 $\mu g/m^3$ Reduction: 24–51 $\mu g/m^3$
	Malmqvist et al., 2018	Malmö (Sweden)	Model of exhaust-free transport	BY: 2016	NO2: reduction of 5.1 $\mu g/m^3$ at individual level from baseline. Baseline: City Hall 14 µg/m3; Roadside 30 $\mu g/m^3$; Background 3 $\mu g/m^3$
	Schram-Bijkerk (2009)	Netherlands	Simulation 1: speed limit reduction from 100 to 80 km/h at 9 highway sections Simulation 2: traffic re-allocation by building a new highway section in the corridor Schiphol-Amsterdam-Almere.	Model: 2020	NO2: 2% reduction
	Xia et al., 2015	Adelaide (Australia)	Decrease km travelled by vehicles (% reduction) Increased cycling: scenarios 1 (5%) and 2 (10%) Increased public transport: scenarios 3 (20%) and 4 (30%) Alternative transport: scenario 5 (40%)	BY: 2010 Model: 2030	PM2.5 ($\mu g/m^3$), annual average (95%CI) Baseline: 0.99 (0.63–2.42) BAU 2030: 1.51 (0.95, 3.69) 5%: 1.38 (0.85, 3.44) 10%: 1.38 (0.84, 3.44) 20%: 1.34 (0.85, 3.21) 30%: 1.19 (0.74, 2.98) 40%: 1.12 (0.68, 2.77)

Abbreviations: BAU = business as usual; BY = base year; GHGs = greenhouse gasses; NDC=Nationally Determined Contribution; ppb = parts per billion; ppbv = parts per billion by volume; SLCP = short-lived climate pollutants.

(Galvis et al., 2015).

One study modelled the effects of reducing tropospheric ozone to the legal limit in areas that were above this limit without targeting a specific sector (Hubbell et al., 2005). Another study simulated PM10 and ozone reductions from multiple sectors, i.e. energy, transport, residential and industrial, or transport and energy (Cifuentes et al., 2001). Overall, PM2.5 was investigated in seven papers, followed by PM10 and ozone in four papers, and NO2 in three papers. One study estimated the effect of four policy scenarios on several air pollutants, including PM2.5, from several sectors, i.e. energy, industry, transport, agriculture, and residential buildings (Kuylenstierna et al., 2020).

Of the tier 2 studies, most papers modelled interventions to the transportation sector, i.e. six studies (Table S2).

3.4. *Policy baselines and temporal scales*

All studies set base years starting from the year 2000 or later to determine the baseline of air pollutant concentrations and associated health effects (Table 1). Eight papers simulated the effects on health that would have occurred if mitigation policies had been adopted in the past (Table 1). Four papers simulated projections of effects on health between 2010 and 2020. One paper evaluated the impact of an existing GHG reducing policy over a period of five years (Perera et al., 2020), one over a period of 20 years (Cifuentes et al., 2001), and one over a period of 30 years (Kuylenstierna et al., 2020). The years between 2030 and 2050 were frequently used for climate change projections (IPCC et al., 2021), but only one paper included in this review simulated health impacts in 2050 (Schucht et al., 2015), and three papers reported on scenarios set in 2030 (Thompson et al., 2016; Xia et al., 2015; Kuylenstierna et al., 2020).

3.5. *Change in GHGs*

In all included papers the GHG mitigation effect was mainly estimated in terms of a reduction of air pollutants such as PM2.5 or NO2, which in turn was used to estimate the effect on air pollutant concentrations and health. Six papers also estimated the effect of the interventions on GHG emissions as well (see scenarios in Table 1).

Abel et al. (2019) reported that according to their model on energy efficiency, there would be a reduction of CO2 of 64.5 Mt (11.6% reduction) in summer, or 258.5 Mt in a year. Kuylenstierna et al. (2020) estimated the impacts of four policy scenarios on GHG emissions and air pollution from several sectors in Bangladesh. The scenarios included three versions of the Nationally Determined Contributions (NDCs), i.e. current, with additional measures, and with potentially additional measures, and one scenario to reduce short-lived climate pollutants (SLCPs). They reported that existing NCDs would reduce CO_2 by 17% in 2030 compared to baseline, but the effect on methane would be negligible (−1%). However, the four policies combined would reduce CO_2 and methane by 25% and 34%, respectively. Schucht et al. (2015) showed that tropospheric ozone increases slightly from 2005 to 2050 in the reference scenario because of the effects of global warming and pollution from outside Europe, but there would be a >85% reduction in the mitigation scenario. Thompson et al. (2016) evaluated a scenario in the energy sector, i.e. the clean energy standard, and a cap-and-trade scenario, and calculated a 14% decrease of carbon between 2012 and 2030 in both cases. Wilkinson et al. (2009) calculated that the replacement of traditional stoves with low-emissions stoves over 10 years in India could reduce the emission of several pollutants equal to 0.5–1 billion tonnes CO2-equivalent. Xia et al. (2015) simulated five scenarios in the transport sector in one Australian city with the reduction of kilometres travelled by vehicles. They showed that the CO2 emitted would be 5060.35 tonnes/day at baseline in 2010 and would increase to 8131.67 tonnes/day in a BAU scenario by 2030. However, the five scenarios resulted in emission reductions that ranged from 5% (7804.78 tonnes/day) to 40% (5516.59 tonnes/day) by 2030.

3.6. Health effects

The effects on child and adolescent respiratory health of GHG mitigation was the most frequently reported outcome (n = 13). Respiratory diseases included asthma, bronchitis, lower and upper respiratory symptoms, and wheeze. Asthma was the most studied respiratory disease (n = 7). In all cases the effects on health were modelled based on changes in exposure to air pollutants: the most investigated exposure was PM2.5 (n = 8), followed by PM10 and ozone (n = 4, each) and NO2 (n = 3) (Table 2).

The policy interventions to mitigate climate change were grouped into four types (Table 1).

The most investigated exposure/outcome relationship was PM2.5/respiratory diseases in 7 papers, followed by NO2 and PM10/respiratory diseases in 3 papers (Fig. 2, Table 2).

3.6.1. Energy sector and asthma

One study estimated that implementing energy efficiency measures that reduce electricity demand in the USA may reduce the concentration of ozone and PM2.5 b y 0.45% and 0.55%, respectively, over one summer (June, July, August), and reduce the number of asthma cases in children aged 6–18 years old by 123,000 (95%CI = −106000, 299,400) and 4600 (95%CI = −270, 10,500), respectively (Abel et al., 2019) (Table 2). One study estimated that 537 asthma cases would have been avoided following the reduction of PM2.5 under the Regional Greenhouse Gas Initiative in the North-East of the USA between 2009 and 2014 (Perera et al., 2020). Thompson et al. (2016) analysed the effects of two different policies to reduce air pollution on three different respiratory outcomes in children 5–6 to 12 years old. They showed that the cap-and-trade approach to reduce emissions from all sectors would be more beneficial than a policy focused on energy only (Table 2).

3.6.2. Transportation sector and asthma

One study on using low-emissions technology for railyard locomotives conducted in Atlanta (USA), showed a reduction of the annual mean incidence of three asthma symptoms in children aged 0–18 years (Table 2) (Galvis et al., 2015). One study conducted in Paris (France), investigated the effect of the implementation of hypothetical low emission scenarios reducing NO2 for one year. The model of the more severe restrictions banning more types of vehicles showed that with a 25–30% reduction of NO2 there would be a reduction of prescriptions to treat asthma among children aged 0–17 years of 2.5% (95%CI = 0.6, 4.4%) (see other scenarios in Table 2) (Host et al., 2020). The health benefit was higher when the model included the towns surrounding Paris within the perimeter of the A86 motorway (4.8%, 95%CI = 1.2, 8.2%). One study set in the USA using two methods to model the health effects of reducing the ozone concentration to below 84 ppb showed that in children under 2 year of age there was a progressive reduction of hospital admissions due to respiratory symptoms over the course of three years (Table 2) (Hubbell et al., 2005). One study reported the reduction of NO2 after simulating exhaust free transport in Malmö (Sweden) would reduce the incident cases of asthma in children aged 5–14 years by 6% from the baseline (Table 2) (Malmqvist et al., 2018). Two studies on two different traffic interventions in the Netherlands showed very little effect by the reduction of NO2 on the attributable cases of wheezing in children aged 7–12 years (Table 2) (Schram-Bijkerk et al., 2009). One study modelling the effects of legislations to improve air quality showed a three-fold decrease of respiratory medications use and lower respiratory symptoms among children aged 5–14 years if additional mitigation measures to keep the average global temperature increase below 2 °C by 2050 are introduced (Table 2) (Schucht et al., 2015).

3.6.3. Other health effects

The reduction of air pollutants through mitigation policies in all sectors examined in this review were estimated to have benefits on other respiratory symptoms in children and adolescents including bronchitis (Adamkiewicz et al., 2021; Cifuentes et al., 2001; Malmqvist et al., 2018; Thompson et al., 2016; Galvis et al., 2015), lower and upper respiratory symptoms (Galvis et al., 2015; Schucht et al., 2015; Thompson et al., 2016; Wilkinson et al., 2009; Xia et al., 2015), and chronic respiratory infections (Staff Mestl et al., 2006) (Table 2). Mitigation policies (leading to reduction of air pollution) were also estimated to decrease hospital admissions and visits for all causes among children aged less than 19 years (2 studies) (Cifuentes et al., 2001; Kan et al., 2004), reduction of adverse perinatal outcomes (2 studies) (Host et al., 2020; Perera et al., 2020), and fewer school absences (2 studies) (Hubbell et al., 2005; Thompson et al., 2016) (Table 2). One study estimated that the U.S. Regional Greenhouse Gas Initiative would decrease the number of cases of autism in children aged 0–18 years (Perera et al., 2020). Four studies estimated that mitigation policies would reduce the number of cases of infant mortality (Cifuentes et al., 2001; Galvis et al., 2015; Schucht et al., 2015; Kuylenstierna et al., 2020).

In tier 2 papers, a variety of health outcomes were used, e.g. DALYs, life expectancy, years of life lost, and QALYs (supplementary material, Table S2). Most tier 2 papers simulated the health impact of decreasing PM2.5 (4 papers), followed by PM10 (2 papers), and ozone (1 paper).

3.7. Economic valuation

Three studies modelled the economic impact of child and adolescent improvements in health resulting from GHG mitigation policies (Table 2). Galvis et al. (2015) calculated the savings based on the willingness-to-pay of to avoid three respiratory outcomes in children for periods of 1 or 6 days. Perera et al. (2020) calculated the savings over a period of five years, estimating that the total saving across the modelled health outcomes in the US states implementing the regional Greenhouse Gas Initiative would range from $97.8 million to $178.8 million, and inclusion of neighbouring states would increase the savings to $191.5 million to $350.1 million. Hubbell et al. (2005) estimated the costs that could be avoided if the tropospheric ozone levels were reduced to the US EPA standard. They estimated that in the year 2000 the cost-of-illness for one hospital admission for respiratory diseases would be $7741, and the cost of school absences would be $75 per day because of missing workdays by one parent who has to care for the sick child.

Three out of seven tier 2 papers calculated the economic impact of the health gains derived from GHG mitigation interventions (supplementary material, Table S2).

3.8. Other characteristics

Most papers fulfilled the criteria of providing basic information on the description of the modelled scenarios, the sources of the data, and tools or functions required to run the simulations (Table S3). On reporting their results, ten papers provided only absolute numbers and did not standardise the health impact using for instance rates per 100,000 people, or percentages. Whilst 11 papers conducted the uncertainty analysis of the parameters, only five also conducted sensitivity analyses. Ten papers briefly discussed the achievability of the scenarios, or how to reach the goals set in the scenarios (e.g., taxation), or the potential to scale up the intervention. Only one paper fulfilled the criterion of indicating where the data and codes were available or stating why they could not be shared.

Eight studies estimated a more realistic implementation of their scenarios with effects occurring in the future, while eight papers simulated the effects after the immediate removal of the air pollutant. Thirteen papers simulated the health impacts of mitigation interventions

Table 2
Health impacts in children and adolescents.

Pollutant	Reference	Age (years)	Population size	Health impact	Health impact	Endpoint valuation. Avoided costs.
NO2	Host et al., 2020	0–17	LEZ enlarged: 995,605 LEZ Paris: n/r	Asthma (prescriptions for treatment)	Annual cases (rate/100,000 people): 43,325 (4352) Percentage of case reduction for 1 year (95%CI) LEZ Paris Ban Low: 1.5 (0.4, 2.6) LEZ enlarged Ban Low: 3.0 (0.7, 5.2) LEZ Paris Ban high: 2.5 (0.6, 4.4) LEZ Enlarged Ban High: 4.8 (1.2, 8.2)	
		Newborns	LEZ enlarged: 70,121 LEZ Paris: n/r	LBW	Annual cases (rate/100,000 people): 1835 (2616) Percentage of case reduction for 1 year (95%CI) LEZ Paris Ban Low: 2.4 (0, 4.7) LEZ enlarged Ban Low: 4.6 (0, 9.1) LEZ Paris Ban high: 4.2 (0, 8.2) LEZ Enlarged Ban High: 7.7 (0, 15)	
	Malmqvist et al., 2018	5–14	n/r	Bronchitis symptoms	Baseline n | Reduced cases (% of baseline n) 957 | 95 (10%)	
				Asthma incidence	354 | 21 (6%)	
	Schram-Bijkerk (2009)	7–12	Children living within 500 m of highway. Before and after intervention: 6882	Wheeze (speed limit reduction)	Attributable cases (95% prediction interval) Before intervention: 391 (69–775) After intervention: 384 (68–763)	
			Before intervention: 4411 After intervention: 4638	Wheeze (traffic re-allocation)	Before intervention: 201 (27–413) After intervention: 206 (28–416)	
PM2.5	Abel et al., 2019	6–18	n/r (source: US census)	Asthma exacerbations	Cases avoided on summer exposure (95%CI) 123,000 (−106000, 299,400)	
	Galvis et al., 2015	Infants	n/r (source: Atlanta census)	Mortality, all causes	Mean reduction in annual incidence (SD) 0.01 (0.01)	
		0–17	n/r (source: Atlanta census)	Hospital admission, asthma	0.02 (0.01)	
		8–12	n/r (source: Atlanta census)	Acute bronchitis	1.4 (0.8)	Willingness to pay, 6 days (age 0–17) $670 ± 500 (mean annual±SD)
		7–14	n/r (source: Atlanta census)	Lower respiratory symptoms	18 (5)	Willingness to pay, 1 day (age 0–17) $370 ± 170 (mean annual±SD)
		9–11	n/r (source: Atlanta census)	Upper respiratory symptoms	25 (10)	Willingness to pay, 1 day (age 0–17) $800 ± 500 (mean annual±SD)
		6–18	n/r (source: Atlanta census)	Asthma exacerbation, cough	340 (164)	
		6–18		Asthma exacerbation, shortness of breath	121 (128)	
		6–18		Asthma exacerbation, wheeze	40 (16)	
	Kuylenstierna et al., 2020	<5	n/r (source: UN DESA)	Premature death	Ambient Household 2010 11,000 30,000 2030 baseline 5000 11,000 2030 NDC existing 5000 11,000 2030 NDC existing+ 5000 11,000 additional 2030 NDC existing+ 5000 5000 additional + possible 2030 NDC + SLCP 4000 5000	
	Perera et al., 2020	≤18	n/r (source: US census)	Pre-term birth	Number of cases avoided between 2009 and 2014 112	$7.5 millions (2009–2014)
				Low birth weight	56	$0.8 millions (2009–2014)

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Table 2 (*continued*)

Pollutant	Reference	Age (years)	Population size	Health impact	Health impact	Endpoint valuation. Avoided costs.
				Asthma	537	$12.1–47.4 millions (2009–2014)
				Autism spectrum disorder	98	$171–294.4 millions (2009–2014)
	Schucht (2015)	0–1	n/r (source: UN World Population Prospects, 2010[a])	Infant mortality	Year Number of premature deaths 2005 1700 2050,200 (reference) 2050,100 (mitigation)	
		5–14	n/r (source: UN World Population Prospects, 2010[a])	Respiratory medications use	Year Days (millions) 2005 4.3 2050 1.0 (reference) 2050 0.3 (mitigation)	
		5–14		Lower respiratory symptoms	Year Days (millions) 2005 211.6 2050 50.4 (reference) 2050 16.2 (mitigation)	
	Thompson et al., 2016		n/r (source: census)	Acute bronchitis	CES | CAT Incidence (95%CI) | Incidence (95%CI) North East 5281 (−193, 10,616) | 2873 (−105, 5781) Other states 1134 (−41, 2290) | 380 (−14, 769)	
				Lower respiratory symptoms	CES | CAT Incidence (95%CI) | Incidence (95%CI) North East 67,239 (32,417, 101,402) | 36,197 (17,518, 54,386) Other states 14,318 (6925, 21,524) | 4657 (2286, 6890)	
	Wilkinson et al., 2009	<5	n/r	Acute Lower Respiratory Infections	Avoided cases 2010–2020 240,000	
	Xia et al., 2015	0–4	n/r	Respiratory disease	BAU 2030: ref. PM2.5 reduction Relative risk | Attributable risk 5% 1.0006 | 0.0006 10% 1.0007 | 0.0007 20% 1.0009 | 0.0009 30% 1.0016 | 0.0016 40% 1.0020 | 0.0020	
		5–14	n/r		BAU 2030: ref. PM2.5 reduction Relative risk | Attributable risk 5% 1.0004 | 0.0004 10% 1.0004 | 0.0004 20% 1.0005 | 0.0005 30% 1.0010 | 0.0010 40% 1.0012 | 0.0012	
PM10	Adamkiewicz et al., 2021	6–18	n/r (source: national census)	Bronchitis	Annual health impact reduction. Cases (% reduction, per 100 k a) Lower Silesia scenario 1: 9602 (27.7%, 331/100 k a) scenario 2: 7303 (21.1%, 252/100 k a) scenario 3: 4628 (13.4%, 160/100 k a) Lodzkie province scenario 1: 9880 (26.8%, 395/100 k a) scenario 2: 8067 (21.9%, 323/100 k a) scenario 3: 6932 (18.8%, 277/100 k a)	
	Cifuentes et al., 2001	<1	n/r (source: US census)	Infant mortality	Cases avoided (95%CI) Mexico city 3065 (1187, 4944) Sao Paulo 701 (271, 1130) Santiago 320 (124, 516) NYC 56 (43, 75) Total 4100 (1600, 6700)	
		<5	n/r (source: US census)	Hospital admissions, all causes	Mexico city 4475 (2282, 6668) Sao Paulo 4638 (2365, 6911)	

(continued on next page)

Table 2 (*continued*)

Pollutant	Reference	Age (years)	Population size	Health impact	Health impact	Endpoint valuation. Avoided costs.
					Santiago 2788 (1422, 4154) NYC -	
		3–15	n/r (source: US census)	Medical visits	Mexico city 87,064 (19,217, 154,912) Sao Paulo 87,377 (19,286, 155,468) Santiago 28,054 (6192, 49,916) NYC - Total 202,000 (45,000, 360,000)	
		8–12	n/r (source: US census)	Acute bronchitis	Mexico city 89,897 (0, 200,805) Sao Paulo 36,157 (0, 80,764) Santiago 20,876 (0, 46,631) NYC 14055 (6838, 20,893) Total 161,000 (0, 350,000)	
	Kan et al., 2004	≤18	n/r (source: Shanghai Bureau of Statistics)	Outpatients visits (pediatrics)	Cases reduced compared to base case scenario Energy efficiency scenario Year Cases reduced (95%CI) 2010 2807 (1010, 4571) 2020 5173 (1855, 8453) Gas scenario Year Cases reduced (95%CI) 2010 13,000 (4686, 21,150) 2020 29,000 (10,420, 47,280) CO2 tax scenario Year Cases reduced (95%CI) 2010 24,660 (8896, 40,050) 2020 48,590 (17,500, 79,080)	
	Staff Mestl et al., 2006	≤14	n/r (source: China Census, 2000)	Chronic respiratory infection	Median percentage reduction (geometric SD) urban no coal: 8.7 (2.5) rural no coal: 80.3 (1.9) rural improved: 57.8 (2.3)	
O3	Abel et al., 2019	6–18	n/r (source: US census)	Asthma exacerbations	Cases avoided on summer exposure (95%CI) 4600 (−270, 10,500)	
	Cifuentes et al., 2001	<5	n/r (source: US census)	Hospital admissions, all cause	Mexico city 721 (79, 1363) Sao Paulo 447 (49, 846) Santiago 153 (17, 289) NYC -	
	Hubbell et al., 2005	<2	n/r (source: 2000 U.S. Census)	Total hospital admissions, respiratory	Cases reduced (5th, 95th percentiles) Quadratic method | Percentage method 2100 (1100, 3100) | 1900 (970, 2800)	Million in 2000 US$ (5th, 95th percentiles) Quadratic | Percentage 16 (8.7, 24) | 12 (7.7, 22)
		5–17	n/r (source: 2000 U.S. Census)	School absences	Cases reduced (5th, 95th percentiles) Quadratic method | Percentage method 970,000 (350,000, 1,700,000) | 890,000 (310,000, 1,500,000)	Million in 2000 US$ (5th, 95th percentiles) Quadratic | Percentage 75 (26, 130) | 58 (23, 120)
	Thompson et al., 2016		n/r (source: census)	Asthma exacerbation	CES | CAT Incidence (95%CI) | Incidence (95%CI) North East 68,971 (−20923, 13,957) | 13,905 (−4220, 28,032) Other states −21416 (−43253, 6483) | 4513 (−1369, 9107)	
				School loss days	CES | CAT Incidence (95%CI) | Incidence (95%CI) North East 50,061 (17,685, 111,203) | 10,083 (−4220, 28,032) Other states −15557 (−34641, −5494) | 3280 (1159, 7296)	

Abbreviations: BAU = business as usual; CAT = cap-and-trade; CES = clean energy standard; FEV1 = forced expiratory volume; FVC = forced vital capacity; IMO-=International Maritime Organization; LEZ = low emission zones; n/r = not reported in paper; ppb = parts per billion.

[a] https://www.un.org/en/development/desa/publications/world-population-prospects-the-2010-revision.html

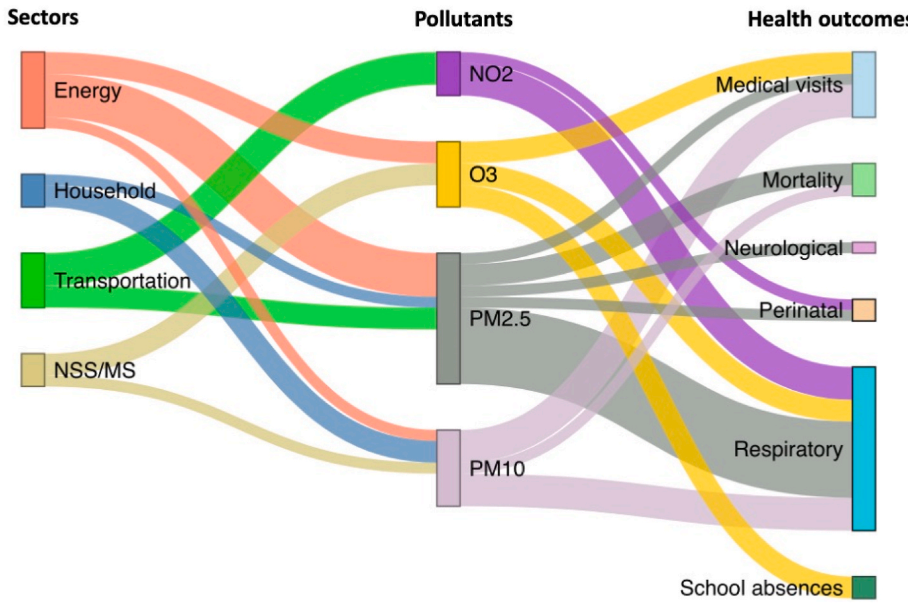

Fig. 2. Sankey diagram showing the relationship between sectors and air pollutants, and between air pollutants and health outcomes in children. The width of each flow linking two nodes is proportional to the number of studies investigating that link. NSS/MS: no specific sector/multiple sectors.

connected with policies or specific existing technologies, and three studies did not specify any policies or technologies.

4. Discussion

Climate change presents a range of direct and indirect threats to child health (Hellden et al., 2021; Bikomeye et al., 2021; Xu et al., 2014). This systematic review summarises the current available published evidence from modelling studies estimating the potential impact of GHGs mitigation strategies on child and adolescent health. We identify largely significant and positive effects on health from climate mitigation interventions, albeit an evidence that is skewed towards changes in air quality.

Indeed, all 16 studies that we identified reported benefits to child and adolescent health from policies that reduce air pollution as a consequence of mitigating the emission of GHGs. Most studies focused on respiratory conditions, with asthma being the most studied outcome, and evidence was also available on birth outcomes, mental health, hospital admissions, all-cause mortality and school days lost. No studies were identified that estimated the effects of GHG mitigation on ambient temperatures, and the consequent effects on health from reduced heat exposure. Nor did we find any studies evaluating the effects on health of interventions to promote dietary changes, with related consequences on the agriculture sector and its emissions. Future studies should include additional sectors that are significant sources of emissions, such as the Agriculture, Forestry and Other Land Use sector, which is responsible for 13–21% of GHG emissions (Nabuurs et al., 2022), and the urban systems, which are drivers of GHG emissions (Lwasa et al., 2022). Additionally, modelling cross-sectoral policies may reveal synergistic effects on reducing emissions and have enhanced positive co-benefits for children's health (Babiker et al., 2022).

Perhaps unsurprisingly given the greater need for climate change mitigation in higher-emission, higher-income settings, 12 of our 16 studies were set in high-income countries (HIC), especially in Europe and USA. Four studies set their models in upper-middle income countries, and one in a lower-middle income country. No studies were set in low-income countries despite their likely vulnerability to the impacts of climate change, the young age of their populations and concurrent development including rapid urbanisation. This geographical limitation may cause an underestimation of the impact of GHG mitigation policies at a global scale. UNICEF has introduced the Children's Climate Risk Index according to which the severity of the health risks is extremely high in the South Asian countries, some of the South-East Asian countries, and most of the African countries between the tropics (UNICEF, 2021). Hence, it is recommended that more studies on the long-term effects of mitigation policies on children's health should be set in countries where the impact of Climate Change is most severe.

Most human activities that contribute to GHG emissions also contribute to adverse effects on air quality, and the likely net benefits for health of climate change mitigation actions because of improved air quality has been reported in numerous studies of the adult population (Gao et al., 2018; Chang et al., 2017; Gallagher and Holloway, 2020; Quam et al., 2017). There have been far fewer studies that have examined the impacts in children, but they all describe the harmful consequences on children health of climate change due to GHG emissions (Hellden et al., 2021; Leffers, 2022; Perera and Nadeau, 2022). UNICEF published reports on the seriousness of the threat that Climate Change poses to children's health and wellbeing (UNICEF, 2015; UNICEF, 2021).

The studies included in our review modelled only some of the possible health effects of mitigating GHG emissions. Important omissions are likely to include estimations of the effect of GHG mitigation on ambient temperatures, and the consequent future health benefits from the reduction of heat exposure (Chapman et al., 2022; Chersich et al., 2020); evaluation of interventions that promote dietary changes and food security, with related consequences on the agriculture sector, its emissions, and consequent health benefits (Willett et al., 2019); estimation of how different building, town planning and transport models affect emissions, physical activity and health (Smith et al., 2017). Additionally, impact on inequalities is an important aspect of studies of climate change mitigation and health, but we found very limited published evidence (Ajanovic et al., 2020). In their review of reviews, Arpin et al. (2021) suggested that climate change may exacerbate child health inequalities between HIC and low- and middle-income countries (LMIC), but quantitative evidence was limited, despite strong descriptive evidence.

These omissions may in part reflect the complexities of determining relevant changes in exposure and exposure-response functions. Lack or insufficient local data (e.g., at a city level) on emission concentrations and the unavailability of local exposure-response functions is a concern particularly for LMIC (Milner et al., 2023). Applying nation-wide emissions levels to cities and/or using exposure-response functions from HIC to LMIC may result in inaccurate estimates of the health effects. Addressing these omissions may also require new modelling methods. For instance, promoting dietary changes can change the environmental impact (including GHG emitted by the agriculture sector) of the food consumed, but assessing this impact could be difficult without knowing the quantities of the ingredients used. Clark et al. (2022) developed a method to overcome this constraint and calculated the impact of 57,000 food products.

This review has several strengths. As far as we know, this is the first systematic review focusing specifically on studies modelling health impacts in children associated with interventions that mitigate GHG emissions and air pollution. Paediatric organisations and researchers have been pointing out the importance of studying child health co-benefits because of their vulnerability and consequences in their adult lives (Committee on Environmental Health, 2007; Council on Environmental Health, 2015; Romanello et al., 2021). The studies included in our review estimated the health co-benefits in three key sectors (i.e., energy, household, and transport) and this review can support policies designed to reduce emissions from these sectors. In addition, the evidence gaps in the current literature above can inform researchers and research funders' priority setting. The main limitation to this work is the heterogeneity of the methodologies and outcomes which did not allow us to summarize the estimates with meta-analyses. Another limitation was our focus on intentional strategies that reduce climate change emissions (i.e., strategies where this is the key objective) rather than those that coincidentally reduce emissions. This strategy may have led to the exclusion of studies which model children's health and climate change mitigation as the consequence of particular actions. A third limitation is that with three exceptions, all other studies estimated short-term effects, so it is difficult to draw conclusions on long-term exposures. This limitation makes it difficult to understand the potentially increasing co-benefits of mitigation policies over the long period, which would provide an even greater justification to mitigate GHG emissions. Finally, most included papers do not report the size of the populations analysed, referring only to the censuses where the population data were obtained. In some cases, it is difficult to appreciate the magnitude of the health impact when only the absolute numbers of changes of cases are provided. All the studies included were in English, so we did not include information available in other languages. Finally, despite the comprehensive search, we may have missed relevant studies because searches are always a balance between sensitivity and specificity, and publication bias may have affected the search result.

5. Conclusion

This review highlights both the sparsity of child-centred evidence for climate action, but also that the existing research literature suggests GHG mitigation interventions are likely to result in significant positive health benefits for children, particularly for their respiratory health.

Our results support increasing calls to consider child health, well-being and rights in research and policies related to climate change (Committee on Environmental Health, 2007; Paulson et al., 2015; Romanello et al., 2021; Clark et al., 2020; Luthen et al., 2021; *General Comment No. 26*, 2023; UNICEF, 2021). Moreover, there is an increasing recognition of children's positive role as agents of change, and the importance of listening to them and working in partnership with them (Juel et al., 2023; UNICEF, 2021; Walker, 2017; Miller, 2007). Studies that include estimations of health effects in children and adults should not aggregate the results across age categories, or at least should keep people <18 years old as a separate category.

Future work focused on long-term health benefits to children of a decarbonised world are vital to planning of climate change mitigation policy making, and to inform evaluation of future climate scenarios.

Additionally, our review reveals the importance of consistent and standardized methods to report health outcomes from modelling studies to allow comparison of results across studies to better advise policy makers on future benefits of mitigation policies. Useful guidelines on how to report modelling results on health effects and climate change mitigation interventions can be found in Hess et al. (2020), for instance.

Further studies in LMICs are needed, where the impact of climate change will be felt more strongly than in HIC (Acevedo et al., 2017). Economic evaluation of gains from mitigation activities could be important especially for LMIC to reallocate resources to adapt to the consequences of climate change.

For a more complete picture of health benefits from GHG mitigation measures, future scenarios should generate near- or mid-term projections to 2030 or 2050 and include both direct and indirect health effects. Lack of prospective scenarios may result in the underestimation of mitigation policies on children's health because climate change emissions have an impact on children's development, in addition to organs functions like in adults (UNICEF, 2015). The time points indicated above are commonly used for future projections, including projections by the IPCC (Riahi et al., 2022).

Contributors

RP and ADD designed the study. RP ran the search. RP, RJ, JM, FK, and ADD screened the records. RP and RJ extracted the data. RP, RJ and JM assessed the risk of bias. RP wrote the first draft of the manuscript. All authors provided critical conceptual input, analysed and interpreted the data, and critically revised the report.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Robert C Hughes reports a relationship with Children's Investment Fund Foundation that includes: consulting or advisory. Robert C Hughes reports a relationship with Clean Air Fund that includes: consulting or advisory.

Data availability

Data for this review were extracted from published papers.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.117102.

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