Understanding the compound risk of heat, humidity and air pollution on human health: A scoping review

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Cover art by Rebeka Ryvola de Kremer.

Designed by Eszter Saródy

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Abstract

Human health is impacted markedly by climate change, particularly by increasing temperatures and air pollutants. Most of the health research in extreme heat and air pollution studies the variable of interest (e.g., temperature) in isolation whilst controlling for other meteorologic and atmospheric variables that can alter human exposure in real time. Previous scoping or literature reviews refer to the necessity of examining the potential interactive effects of weather conditions and air pollution to better characterize climate-related health outcomes. However, there are still a limited number of studies that examine compound effects.

We searched five online databases – four for peer-reviewed literature (Medline, Excerpta Medica dataBASE (EMBASE), Scopus and Global Index Medicus (GIM)) as well as one grey literature site (ReliefWeb) – using prearranged keywords combining compound exposures of air pollution, extreme heat, humidity and a health outcome. A total of 506 papers matched our search criteria of which 33 were included in the final synthesis. Three papers (9 per cent) touched on the compound impacts of heat, humidity and air pollution, while 16 (48 per cent) analysed heat and air pollution and 17 (52 per cent) investigated heat and humidity. Papers could be assigned more than one category. Overall, papers found worse health outcomes during periods that coincided with compound exposure for mortality, cardiovascular conditions, respiratory and pulmonary conditions, kidney function, birth complications, and physiological or cognitive functions.

It is clear that although the health risks of air pollution, heat and humidity are well established individually, evidence on compound risks is lacking. This paper emphasizes that a more complex understanding of heat is necessary, including an assessment of the compound effect of humidity with temperature and air pollution. With the increase in the frequency, severity and duration of heatwaves and air pollution, there is a greater need to examine the full range of interactive impacts on human health for setting future research agendas and implementing appropriate actions.

Key messages

This scoping review of over 20 years of peer-reviewed literature shows that the compound impact of heat, humidity and air pollution on health is largely absent from the research landscape.

The research that does exist shows that heat, humidity and air pollution have additive effects on cardiovascular, respiratory, maternal and neonatal health, and overall mortality.

Complex interactions between temperature and environmental variables need to be considered for extreme heat policy and interventions to reduce the health impacts of extreme heat accurately and efficiently.

Increased effort should be made to expand the scope of heat and air pollution research to include:

1. higher granularity and quality of meteorological and air quality data to better assess individual risk levels
2. health outcomes beyond cardio-respiratory mortality and morbidity
3. broader geographical scope of research into understudied regions e.g., the Middle East and North Africa (MENA)
4. evaluations of earlier health–heat mitigation and adaptation interventions

Background

Climate change and global environmental change impacts human health, most notably – and with a high degree of certainty – via increasing temperatures and air pollution (IPCC, 2022). Of all natural hazards globally, heatwaves and extreme temperatures lead to some of the highest mortality (Petkova *et al.,* 2014). Longitudinal epidemiological studies, predominantly in high income countries, on heatwaves and extreme heat show a clear pattern between increased temperature and excess mortality (Ebi *et al.,* 2021). Furthermore, air pollution causes significant morbidity and contributes to 9 million deaths annually (Fuller *et al.,* 2022; Manisalidis *et al.,* 2020). However, the majority of health research on extreme heat and air pollution studies the variable of interest (i.e., temperature, specific pollutants) in isolation, controlling for other meteorologic and atmospheric variables that can alter human exposure in real time (Sun & Zhu, 2019; Zafeiratou *et al.,* 2021).

Without mitigation and adaptation, current global temperature extremes will be exceeded (Tong *et al.,* 2021). High temperatures contribute to the production of ozone which further traps heat and air pollutants contributing to excess respiratory and cardiovascular mortality (Tong *et al.,* 2021). Exposure to chronic extreme heat is associated with kidney disease, adverse mental health and a reduction in labour productivity (Haines & Ebi, 2019; Tong *et al.,* 2021). Heatwaves, commonly understood to be temperatures above the normal range and lasting for several days, can have a significant impact on excess mortality (Guo *et al.,* 2018). The 2010 Russian heatwave, for example, was responsible for 55,000 deaths (Guo *et al.,* 2018).

Humidity alters human heat tolerance by reducing the effectiveness of sweat evaporation, a core mechanism for human thermoregulation (Raymond *et al.,* 2020). When air temperature is above core body temperature, evaporation is the only mechanism for cooling as convection and radiation are no longer effective (Davis *et al.,* 2016). Although humidity is an important variable for human physiology, its impacts are often not studied in isolation, either being removed as a confounder or studied in combination with heat or air pollution (Davis *et al.,* 2016). Further, some literature suggests humidity can play a role in the formation of different air particles. Notably, the formation of organic aerosol, a component of PM2.5, can be enhanced at high humidity levels (Davis *et al.,* 2016). Therefore, humidity can influence the health impacts of high temperatures, by reducing the physiological capacity to adapt, and air pollution by increasing the presence of air pollutants, both of which can contribute to complications of cardio-respiratory conditions and excess mortality.

Air pollution has long been tied to negative health outcomes. The health impacts can vary by pollutant (particulate matter of less than 2.5 micrometers (PM2.5) and 10 micrometers (PM10), nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3) and sulphur dioxide (SO_2) with the most common health conditions including chronic obstructive pulmonary disease (COPD), asthma, bronchiolitis, lung cancer and cardiovascular and nervous system complications (Manisalidis *et al.,* 2020). Other health impacts from exposure to air pollution include diabetes and adverse birth outcomes (Manisalidis *et al.,* 2020). It is common for air pollution to co-occur with extreme heat due to overlapping meteorologic drivers found in slow-moving, high-pressure weather systems (Rahman *et al.,* 2022; Schnell & Prather, 2017). The low wind speed and low precipitation that often accompanies heatwaves also contribute to the increased accumulation of air pollutants (Schnell & Prather, 2017). High temperatures increase the presence of biogenic volatile organic compounds, a type of hydrocarbons naturally produced by plants, which contribute to the production of both O_3 and PM2.5 when in contact with anthropogenic air pollution (Loreto & Fares, 2013). Further, increasing energy demand to operate cooling infrastructure like air conditioning increase greenhouse gas emission levels during heatwaves (Schnell & Prather, 2017).

Limited literature on the additive nature of temperature, humidity and air pollution shows that it has not been well studied to date. When compound effects are examined, it has solely been between temperature and air pollution. For example, a scoping review by Al Ahad *et al.* (2020) only examined compound effects of temperature and air pollution incidentally and did not find any papers that also included humidity. The authors noted that only nine of 112 articles accounted for the effect of temperature on air pollution and health or vice versa. Grigorieva and Lukyanets (2021) in their research note that almost all papers reviewed provided consistent evidence of a synergistic effect between temperature and air pollution on enhanced respiratory morbidity and mortality. Moreover, while humidity is mentioned in the papers reviewed (e.g., the use of relative humidity to express apparent temperature) it is not directly included (Analitis *et al.,* 2018; Fever *et al.,* 2022).

All three of these variables are independently associated with adverse health impacts on complex and enmeshed biological systems. Rising temperatures and the changing frequency and duration of heatwaves, as a result of anthropogenic climate change, means that understanding the full range of variables that can alter human exposure to heat is crucial to implement the most relevant and effective actions. As such, this scoping review aims to consolidate and assess the existing literature on the compound risk of extreme heat, humidity and air pollution on human health to identify knowledge gaps that could guide future research, interventions and policy on this intersection.

Methodology

Search strategy

We followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension guidelines for Scoping Reviews (PRISMA-ScR) (Peters *et al.,* 2020). We searched five online databases, four for peer-review literature (Medline, EMBASE, Scopus and GIM) and one grey literature site (ReliefWeb), using prearranged keywords. The search terms combined compound exposures of air pollution, extreme heat, humidity and a health outcome (*see* Table 1). The search was completed in one day on 9 November 2022. Results were combined and stored using Endnote; duplicates were removed using software and confirmed manually. Relevant articles were then identified by screening titles and abstracts. Full texts were reviewed and disagreements were resolved by consensus. A full list of included papers can be found here.

Table 1. Search keywords

Exposure		Exposure		Exposure		Outcome
Heat		Air pollution		Humidity*		Health
Heatwave*		Air quality		Wet bulb temperature		Disease
						Morbidity
Extreme heat	AND	Air Quality Index (AQI)	AND		AND	Life expectancy
Extreme temperature		Particulate matter		Universal Thermal Climate Index (UTCI)		Death
						Mortality
Temperature*		Pollutant*				Respiratory
						Cardiovascular

Inclusion criteria

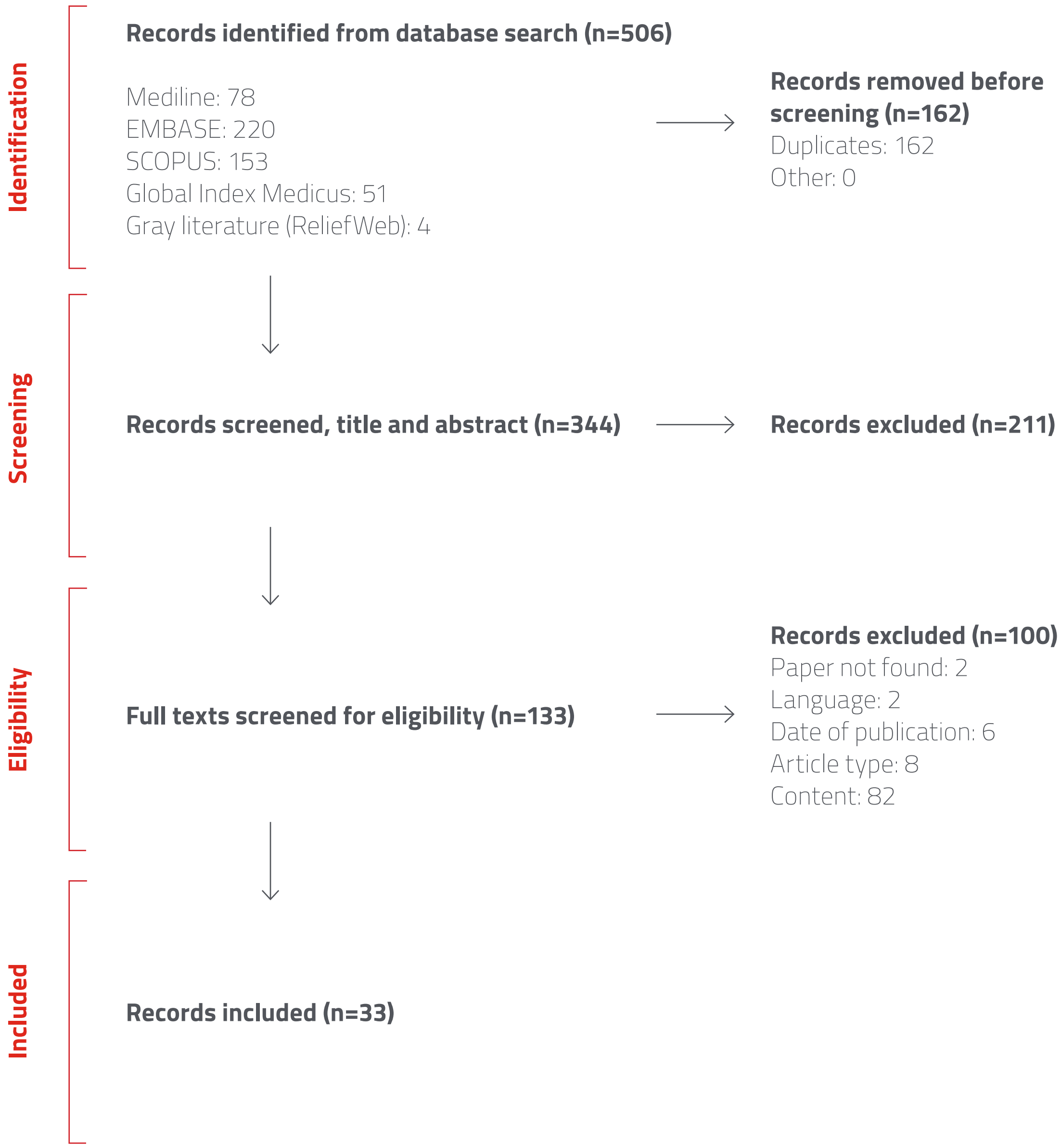
The following inclusion criteria were applied: articles must be peer-reviewed, published in English, and investigate the health outcomes of air pollution, humidity and extreme heat in combination. Articles were included if they were published between 2000 and 2023. There was no limit on geographic location. Articles were excluded if they did not include quantified measurements (e.g., PM2.5 levels) of at least two of the variables of interest (air pollution, humidity and extreme heat) and if they did not incorporate quantified impacts on human health (e.g., mortality). Conference abstracts, protocols, books or book reviews were excluded.

Screening process

Two reviewers (D.O. and S.C.) screened titles and abstracts to identify qualifying articles using the inclusion criteria. Five reviewers (D.O., S.C., J.K., L.P. and T.A.) then single screened titles, with a handful of papers double screened as abstracts and full article texts; disagreements were resolved by consensus. Data was extracted into Excel using a pre-agreed form (study location, region, study design, study period, sample size, study population, gender of study population, air pollution metric, heat metric, humidity metric, measured or evaluated health outcome, significant findings by variable, significant findings on compound effects, suggested recommendations on mitigation or adaptation measures to reduce health impacts, non-significant association) and analysed for research gaps on exposures, health outcomes and preventative measures.

Results

Figure 1. PRISMA flowchart



A total of 506 papers matched our search criteria of which 33 were included in the final synthesis (Figure 1). Three papers (9 per cent) investigated the compound impacts of heat, humidity and air pollution, while 16 (48 per cent) analysed heat and air pollution and 17 (52 per cent) analysed heat and humidity. No papers focused on the intersection of humidity and air pollution. Papers could be assigned more than one category if their findings covered more than one compound interaction. Findings on individual variables were not included in the synthesis.

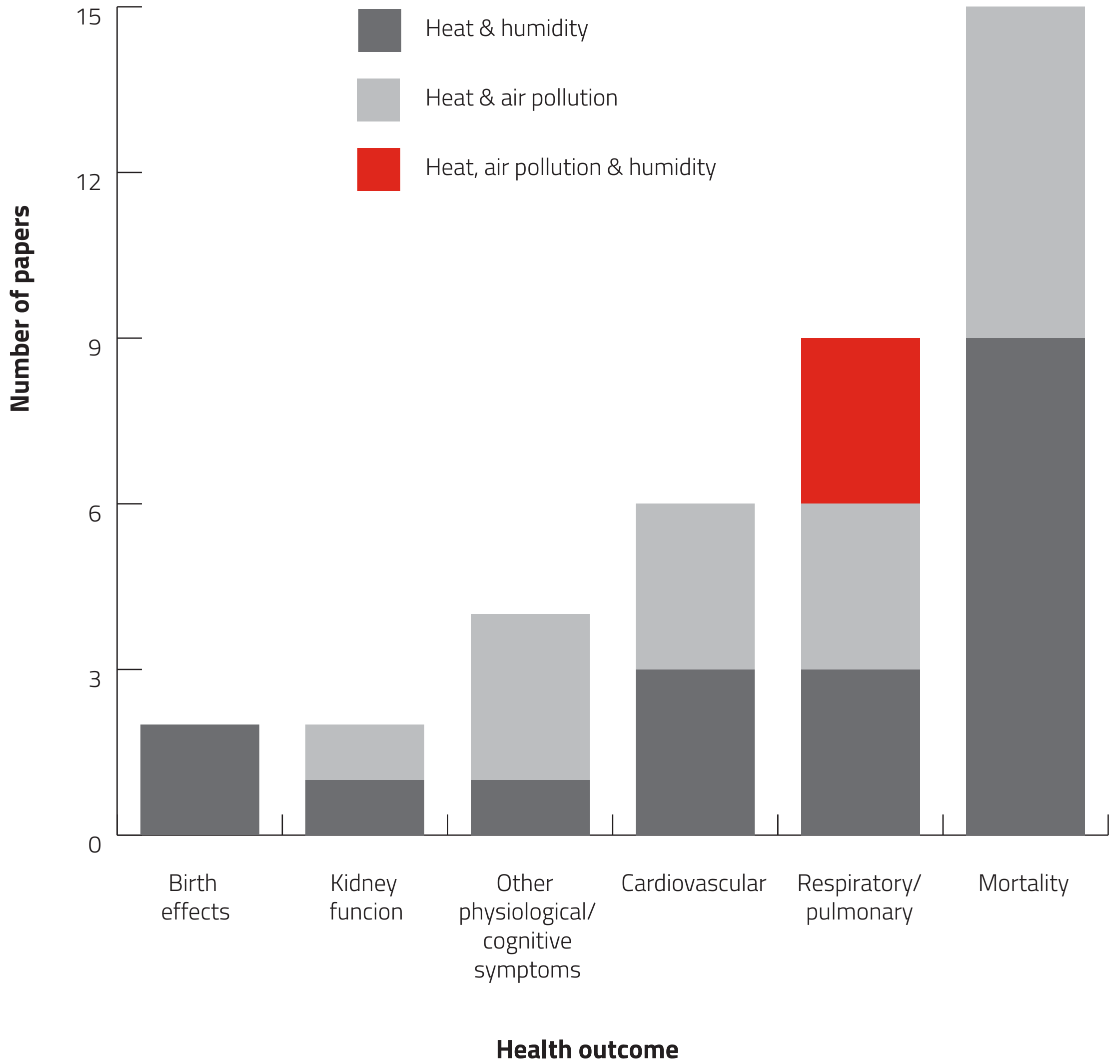
Studies were predominantly conducted in Asia (n= 13) followed by North America (n= 10), Europe (n= 5) and South America (n= 3) (see Figure 2). Eighteen papers retrieved were in high-income countries and 30 papers conducted city-level analysis with some employing multi-city design (n= 7). There was just one paper in the MENA region (Sohrab *et al.,* 2020) and one in sub-Saharan Africa (Lokotola, Wright & Wichmann, 2020) that examined the compound impacts of two variables on health outcomes.

Figure 2. Geographical distribution of reviewed literature

The majority of papers retrieved were gender inclusive in their study design (n= 29) with some focusing only on male (n= 3) or female (n= 1) study populations. As indicated in Figure 3, age groups under study varied, with the majority of papers working with age-inclusive data (all ages) (n= 19) followed by adults (n= 8), the elderly (n= 5) and infants/children (n= 4). One study looked at both adults and children (Mohammad-Shahriar *et al.* 2018) while two papers looked at both all-age data and infants (Son *et al.* 2019, Li *et al.* 2021). Among the three papers accounting for the compound impact of all three variables, one included all age groups (Pande *et al.,* 2002) with two focusing on the elderly population. Of the study population, public data (e.g., population or mortality data) was the most prevalent (n= 15), followed by patients (n= 10), students (n= 3), mother–newborn pairs (n= 2), and population enrolled in health programmes (n= 2). The majority of papers employed observational study design (n= 30) with sample size ranging from 69 people (McCormack *et al.* 2016) to 9,246,807 people (Yang *et al.* 2018). Three papers with experimental study design had a study population ranging from 30 (Tu *et al.* 2021) to 360 (Silva *et al.,* 2020).

The majority of papers focused on mortality as a health outcome (n= 14) followed by respiratory (n= 7) and cardiovascular (n= 5) conditions, other physiological or cognitive functions (n= 4), birth effects (n= 2) and kidney functions (n= 2). Papers measuring compound impacts of the three variables focused on respiratory (n= 2) and cardio-respiratory (n= 1) conditions, while papers on the joint impact of two variables (heat and air pollution; heat and humidity) focused largely on mortality (n= 9; n= 6), cardiovascular conditions (n= 3; n= 3) and respiratory conditions (n=3; n=3). Other significant health outcomes include various physiological and cognitive symptoms for compound impacts from heat and humidity (n= 3).

Figure 3. Reviewed literature by health outcome



Nineteen papers accounted for air pollution data. Air pollution was quantified in eight different types of measured chemicals or particulates (PM2.5, PM10, NO, NO_2, CO, CO_2, O_3, SO_2) with the majority (n= 15) measuring more than one type of pollutant. Of 19 papers that assessed the combined impacts including humidity, all papers used relative humidity with two additionally specifying the use of wet bulb temperature (Silva *et al.* 2020, Singh *et al.* 2016). All 33 papers retrieved quantified heat variables, with the majority (n= 23) using ambient temperature, followed by apparent temperature (n= 5) (Basu *et al.* 2015, Basu *et al.* 2017, Krstić 2011, Lokotola, Wright & Wichmann 2020, Zhang *et al.* 2014), heat index (n= 4) (Basu, Feng & Ostro, 2008, Huang *et al.,* 2021, Semenza *et al.,* 2008, Son *et al.,* 2019), and humidex (n= 1) (Singh *et al.,* 2016).

Health impacts of compound risk of heat, humidity and air pollution

Three out of 33 papers had significant findings on the compound risk of heat, humidity and air pollution on human health (Machin *et al.,* 2019; Pande *et al.,* 2002; Lepeule *et al.,* 2018). Yet, the compound effects of all three variables were not the central research of any of these papers. All three papers were observational (two retrospective cohorts and one prospective cohort (Lepeule *et al.,* 2018) studies and focused on urban populations in the following cities: Delhi, India (Pande *et al.,* 2002), Cuiabá, Brazil (Machin *et al.,* 2019), and Boston, USA (Lepeule *et al.,* 2018). Machin *et al.* (2019) focused specifically on people over the age of 60 while Pande *et al.* (2002) did not limit population by age. Lepeule *et al.* (2018) studied males aged 21–80.

Both Pande *et al.* (2002) and Machin *et al.* (2019) focused on medical care utilization (hospital or out-patient visits) for respiratory conditions, with Pande *et al.* (2002) also studying cardiovascular conditions. Both studies found that there was an inverse relationship between air pollution and heat and humidity variables. Although both studies primarily focused on air pollution impacts, Machin found that hospitalizations of patients over 60 for respiratory conditions were highest when temperature, relative humidity and rainfall were low. This correlated with a high proportion of wildfires and increased pollution (Machin *et al.,* 2019). Further, Pande *et al.,* (2002) found that sulphur dioxide (SO_2), carbon monoxide (CO) and nitrogen oxide (NO_x) were not significant predictors of cardio-respiratory events when temperature and humidity were included in the model.

Similarly, Lepeule *et al.* (2018) looked at pulmonary function (forced vital capacity and forced expiratory volume) in relation to exposure to heat and humidity levels. The paper suggests a stronger association between high temperature and high humidity with lower pulmonary function in patients with high exposure to black carbon.

Due to the small number of papers that analysed the compound risk of all three variables of interest (heat, humidity and air pollution), we also looked at papers that analysed the compound risk of two variables: heat and air pollution; and heat and humidity. None of the papers retrieved analysed the compound risk of humidity and air pollution.

Health impacts at the intersection of heat and air pollution

Sixteen of the retrieved papers analysed and discussed the compound impact of at least one air pollution variable and heat on a measured health outcome. Generally, studies indicated that there were measurable compound effects of temperature and air pollution on health outcomes such as declining lung function (McCormack *et al.,* 2016), increase in mortality (Benmarhnia *et al.,* 2014; Rodrigues *et al.,* 2017; Dardir *et al.,* 2023), cardiac arrest (Tobaldini *et al.,* 2020), hospital admissions (Ruiz-Paez *et al.,* 2023; Dardir *et al.,* 2023) and emergency department (ED) visits for asthma (Mohammed-Shahriar *et al.,* 2018). For example, Tobaldini *et al.* (2020) found a maximum effect of a 14.9 per centt increase in cardiac arrest events when both air temperature and PM (2.5 and 10) levels were high. However, some correlations and associations were non-significant. For example, Rodrigues *et al.,* (2017) found that mortality and hospitalization due to cardiovascular disease (CVD) had a negligible correlation with the compound effects of meteorological and pollution variables.

The interactive effect of cold temperatures with air pollution varied, with one paper finding no interactive effects between PM10 or O_3 and low temperatures on mortality (Breitner *et al.,* 2014) and two papers finding significant compound effects of cold temperature and air pollution on health (Lokotola, Wright & Wichmann, 2020; Wu *et al.,* 2022). Notably, Wu *et al.* (2022) found that a 10 micrograms per cubic metre (10 µg/m^3) increment increase in exposure to NO_2 at low temperatures increased the frequency of hospital visits due to chronic kidney disease (CKD) by 4.3 per cent, demonstrating a stronger association between NO_2 and low temperatures than medium or high temperatures. Overall, temperature and NO_2 had a statistically significant multiplicative effect on CKD hospital admissions. While this study also collected air pollution data on five other air pollutants, no correlation was found between these and CKD-related hospital visits. One study found that different sources of air pollution had associations with different temperature levels (Lokotola, Wright & Wichmann, 2020). For example, SO_2 had a significantly stronger effect on CVD hospital admissions on cold days whereas NO_2 had a significant effect on warm days.

Three studies (Basu, Feng & Ostro, 2008; Sohrab *et al.,* 2020; Tu *et al.,* 2021) found no significant compound or interactive effects between air pollutants (PM2.5, P10, O_3, NO_2, CO, CO_2, SO_2) and heat on the chosen health metrics (mortality, cardiovascular functioning, cognitive functioning). For example, Sohrab *et al.,* (2020) found no clear evidence for the modification of the effect of cold or heat on mortality due CVD or respiratory disease by air pollutants. One paper (Brietner *et al.,* 2014) only found interactive effects between air pollution and heat at warmer temperatures, and no effects at low temperatures.

These papers indicate that there needs to be an improved understanding of the impact of indoor temperature and air quality, for example, as indoor cooling or filtration may improve respiratory health in warmer months (McCormark *et al.,* 2016). Increasing the number and sensitivity of atmospheric monitoring stations could improve overall data quality used to inform early warning systems and forecasts (Rodrigues *et al.,* 2017). Moreover, using this data could be used to forecast increases in emergency calls or hospital admissions, allowing institutions to prepare and allocate additional human and technical resources in response (Tobaldini *et al.,* 2020). Improving understanding of the interactive effects of air pollution and heat on health can contribute to an evidence base for the stipulation of air quality standards or other environmental control requirements, as well as for the expansion of heatwave action that account for the varying impacts of heatwaves in environments with different levels and sources of air pollution (Ruiz-Paez *et al.,* 2023). Finally, knowledge from these studies can be used to reduce the potential or actual health burden of the diseases or conditions analysed (Wu *et al.,* 2022).

Health impacts at the intersection of heat and humidity

Seventeen papers were retrieved with a focus on heat and humidity. The compound impact of high heat and high humidity was linked with an increase in all-cause, respiratory and circulatory mortality (Yang *et al.* 2018; Zhang *et al.* 2014; Basu *et al.* 2015), preterm birth (Li *et al.,* 2021), cardiovascular conditions and disease risk (Huang *et al.,* 2021; Basu *et al.,* 2017), and kidney dysfunctions (Singh *et al.,* 2016).

The compound interaction between temperature and humidity was linked to increased health risks. Six papers discussed the compound impact of heat and humidity on mortality. High heat and low humidity were found to increase mortality from circulatory and respiratory causes up to 28.4 per cent for every degree of temperature rise above 36.5°C for the elderly population (Díaz *et al.,* 2002) and associated with morbidity and mortality from cardiovascular diseases (Rodrigues *et al.,* 2017). High heat and high humidity were correlated with non-case-specific daily mortality (Yang *et al.,* 2018), all-season mortality (Krstić, 2011), 3.5 per cent higher mortality at higher apparent temperature and 6.2 per cent higher mortality rate during heatwaves (Zhang *et al.,* 2014), and increased risk of all-cause and respiratory mortality for neonates and circulatory mortality for post-neonates (Basu *et al.,* 2015). Exposure to high heat and humidity during the whole pregnancy was further linked to an increased risk of preterm birth, and exposure during the first and second trimesters was linked to decreased birth weight (Li *et al.,* 2021). Low temperature and high humidity (above 79 per cent) were consistently associated with COPD hospitalizations (Li *et al.,* 2021) and high temperature and humidity were associated with incidences of cardiovascular conditions, ventricular tachyarrhythmia (low heat index (HI) more strongly associated) (Huang *et al.,* 2021) and increased risks of kidney dysfunctions (Singh *et al.,* 2016). Other studies found correlations between high apparent temperature and an increase in Lipoprotein A, a marker for cardiovascular disease risk (Basu *et al.,* 2017) and increased blood pressure, heart rate, and decreased cognitive performance (Silva *et al.,* 2020; Tian *et al.,* 2021). Two papers found no association between humidity/heat and chronic bronchitis diagnosis (Figgs *et al.,* 2020) and lung function (Lepeule *et al.,* 2018).

The papers identified various vulnerable groups. Díaz *et al.* found that women over 75 were particularly vulnerable to circulatory-cause mortality in high heat and low humidity conditions (Díaz *et al.,* 2002), while Yang *et al.* found that urban populations with lower levels of educational attainment were at greater susceptibility to non-case specific mortality in high heat and high humidity conditions (Yang *et al.,* 2018). For COPD susceptibility, Li *et al.* (2021) discussed the higher vulnerability of female and elderly patients under low temperature and high humidity conditions, and patients with electrical storm were found to be at an increased vulnerability to be diagnosed with ventricular tachyarrhythmia under high temperature and high humidity conditions (Huang *et al.,* 2021).

The data gathered through these studies on the interactive effect of heat and humidity can be used to optimize early warning systems as well as identify relevant mitigation and adaptative actions by specifying the potential negative health outcomes or health needs that arise from these interactions contributing to a reduction of the overall health burden of climate change. The identified measures include reallocating medical and social resources in anticipation of climate change events and in recognition of the specific vulnerability of population sub-groups (Huang *et al.,* 2021), establishing heat advisory systems on health-related behaviours (Semenza *et al.,* 2008), developing an early warning system that informs the public on the health impacts of climate change such as heatwaves, and the design of community-based health programmes (Yang *et al.,* 2018).

Discussion

This scoping review expands on prior research by considering the compound effects of heat, humidity and air pollution on health. The necessity to study this interaction is suggested in the discussion of previous scoping or literature reviews that do not analyse this intersection themselves (Al Ahad *et al.,* 2020; Grigorieva & Lukyanets, 2021; Song *et al.,* 2020). Of the 33 papers we analysed, three papers investigated the compound impacts of all three variables (Machin *et al.,* 2019; Pande *et al.,* 2002; Lepeule *et al.,* 2018) and found notable but varied impacts on respiratory (n=2) and cardio-respiratory (n= 1) conditions that suggest complex interactions between the three variables and health outcomes. Sixteen papers looked at the joint impact of heat and air pollution and found measurable compound impacts on health outcomes including mortality (n= 8), respiratory or pulmonary conditions (n= 3), cardiovascular conditions (n= 3) and kidney function (n= 1). Seventeen papers examined the combined effect of heat and humidity on human health and found high heat and high humidity were associated with increased mortality (n= 4), cardiovascular conditions (n= 2), respiratory or pulmonary conditions (n= 1), birth complications (n= 1) and kidney dysfunction (n= 1), while high heat and low humidity conditions were linked with increased mortality (n= 2).

Heat is often conflated with high air temperature, which is unlikely the sole cause of heat stress (McGregor & Vanos, 2018). This scoping review aims to fill a research gap given the sparse and often inconsistent way humidity is incorporated and interpreted in health studies (Davis, McGregor & Enfield, 2016). Thus, this paper emphasizes that a more complex understanding of heat is necessary, including an assessment of the compound effect of humidity with temperature and air pollution.

Although the health risks of air pollution, heat and humidity are well established individually, it is clear that the evidence on compound risks is lacking. Studies on compound risk are likely rare due to the increased complexity of research methods required, data quality barriers and difficulties in inferring causation. However, there is an increasing trend that research on compound risk is becoming more common, as 75 per cent of reviewed papers were from 2015 onwards. This scoping review confirms the conclusions of previous papers, which note that using indices that combine air pollution, heat and humidity data in a multiplicative way can improve understandings or predictions of health effects (Fever *et al.,* 2022).

Further, health research on air pollution, heat and/or humidity is limited by weather and air pollution monitoring data. By not using apparent temperature or heat indexes, the temperature measurement is already less relevant to human health due to the role of humidity in human thermoregulation (Raymond, Matthews & Horton, 2020). Further, the use of relative humidity instead of absolute humidity can lead to misunderstandings in result interpretation. Colder temperatures often have higher relative humidity – not because there is more water vapour in the air but because it is closer to 100 per cent saturation (Davis, McGregor and Enfield, 2016). Integrating absolute humidity into heat and health research will be critical to the relevancy of the findings.

The literature also presented difficulties ensuring that population-level results are applied appropriately at an individual level (Sharovsky, César & Ramires, 2004; Lepeule *et al.,* 2018; Fujii *et al.,* 2020; Huang *et al.,* 2021; Li *et al.,* 2021; Rodrigues *et al.,* 2017; Son *et al.,* 2019). Potential variance in individual exposure may lead to bias in the results by over- or underestimating the real effect of compound risk on patients. Personal monitoring devices could be used to mitigate this difference by confirming the true values experienced by subjects.

Existing literature focuses heavily on mortality and morbidity of respiratory and cardiovascular conditions, measured by emergency department and hospital visits. The emphasis of research on cardio-respiratory outcomes could perhaps result in other important health impacts being overlooked that are less represented in current literature. It is unclear if this is perhaps due to confirmation or publication bias.

Research recommendations

This review presents numerous gaps that should be explored in future research. First, research on compound risk and effect modification related to heat exposure needs to be further pursued (Brietner, 2014). Second, research needs to evaluate the way in which humidity is included in research in order to produce the most relevant results on health outcomes. Using apparent temperature and heat indices instead of ambient temperature measurements (such as mean temperature) and using absolute humidity instead of relative humidity could help in this regard (Pyrgou & Santamouris, 2018; Davis, McGregor & Enfield, 2016). Third, health research on heat is limited by the quality and granularity of meteorological data. There is a need to increase the use of personal monitoring of meteorological and air quality data to advance health research at this intersection (Piel, 2017). Fourth, we suggest that more research focus on health outcomes outside of cardio-respiratory mortality and morbidity. Fifth, more research focused on understudied regions (e.g., MENA) is needed to address significant knowledge gaps. Lastly, the lack of evaluation research on heat–health interventions is a concern. Evidence on effective interventions at the intersection of heat, humidity and air pollution should be a priority for researchers, policymakers and practitioners.

Intervention and early action recommendations

Mitigation and adaptation techniques were not studied by the papers in this review. However, several papers suggested the use of integrating forecasting systems, advisory systems or early warning systems into monitoring plans, especially as it relates to planning for human, technical and medical resources (Pyrgou *et al.,* 2018, Semenza *et al.,* 2008, Tobaldini *et al.,* 2020, Yang *et al.,* 2018). Existing early action protocols of the International Red Cross and Red Crescent Movement and other humanitarian actors, and action plans of national governments, address many of these variables individually including volcanic ash and heatwaves. Early action protocols could be expanded to better account for the compound effects of air pollution, heat and humidity. Exploration of rare extreme compound events such as heatwaves during high pollution post-disaster reconstruction periods could add value to contingency plans. Further investigation of the relationship between the compound effect of these three variables on tolerable thresholds should be pursued.

Due to the dual benefits of reducing air pollution on health and climate mitigation, numerous policies address this intersection. The Climate and Clean Air Coalition (CCAC) identifies 25 clean air measures that would reduce global warming by 0.33°C by 2050 and improve premature mortality from air pollution exposure by promoting the use of public transportation and electric vehicles, managing agricultural crop residues and fertilizer application, and incentivizing the extended use of renewable power sources (UNEP, 2019). It will be important for policies at the city, regional and national levels to go beyond mitigation efforts and begin to implement adaptation efforts to respond to the increased health burden found at the intersection of heat, humidity and air pollution.

Limitations

This paper had several limitations. First, our main aim was to look at the compound effects of three variables on health: heat, air pollution and humidity. Our search criteria followed this aim by requiring results to incorporate key words of all three components. Due to the low number of papers that effectively studied the compound risk of all variables, we expanded our inclusion criteria to discuss the compound effects of two variables (heat and air pollution; heat and humidity) using the results from the initial search. Therefore, the literature included in these two sections is not representative of the total literature landscape. For example, a PubMed search using our search methodology, but only including search terms for heat and humidity exposures, returns 227 peer-reviewed articles between 2000 and 2023.

Evidence on the compounding effect of these exposures is not easily generalizable due to studies limited to specific regions, study populations, and differing variables and methodologies. None of the papers overlapped in terms of the research question and target population. This makes it extremely difficult to have generalizable results across regions and populations. Further, only one paper (Lokotola, Wright and Wichmann, 2020) took place in sub-Saharan Africa and one in the MENA region (Sohrab *et al.,* 2020), adding to limitations on geographical variability and further impacting the generalizability of findings.

The interactions between weather and air pollution and health outcomes are complex. There are additional meteorological and pollution variables that we did not examine in this paper that could further influence human health outcomes. Atmospheric pressure, wind speed and other sources that can influence air quality, including wildfire smoke, volcanic ash, industrial sites and traffic patterns were not included in our search criteria or directly sought out.

The paper was a scoping review and, therefore, did not analyse the quality of the methodology of the papers included. The results of the papers included were represented by their authors without further analysis on the strength of the findings.

Conclusion

This scoping review of over 20 years of peer-reviewed literature shows that the compound risk of heat, humidity and air pollution is largely missing from academic discourse. It is clear that heat, humidity and air pollution have additive effects on cardiovascular, respiratory, maternal and neonatal health, and overall mortality. With the increase in the frequency, severity and duration of heatwaves and air pollution from anthropogenic activities and climate change, there is a greater need to examine the full range of interactive impacts on human health for setting future research agendas and implementing appropriate actions. It is imperative for research, action and policy to strongly consider the implications of compound exposure to high temperature, humidity and air pollutants on health to effectively reduce the health burden and excess mortality during periods of extreme heat. Without proper monitoring and evaluation of interventions, it will be impossible to take the urgent action required to reduce mortality and morbidity related to heat, air pollution and humidity.

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