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RESEARCH ARTICLE

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Evaluation of the impact of heat stress on the occurrence of occupational injuries: Meta-analysis of observational studies

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Background: Growing evidence indicates that the exposure to high heat levels in the workplace results in health problems in workers. A meta-analysis was carried out to summarize the epidemiological evidence of the effects of heat exposure on the risk of occupational injuries.

Methods: A search strategy was conducted to retrieve studies on the effects of climate change on occupational injury risk. Among the 406 identified, 5 time-series and 3 case-crossover studies were selected for meta-analysis.

Results: Pooled risk estimates for time-series and case-crossover studies combined, and then separated, were 1.005 (95%CI: 1.001-1009), 1.002 (95%CI: 0.998-1.005), and 1.014 (95%CI: 1.012-1.017), respectively. Subgroup analyses found increased risks (not statistically significant) for male gender, age <25 years and agriculture.

Conclusions: The present findings can orient further research to assess the effects of heat at workplace and consequently to establish better health policies for managing such exposure in at-risk regions.

KEYWORDS
climate change, global warming, heat wave, occupational injury, temperature

1 | INTRODUCTION

With climate change, mean annual air temperatures are getting hotter in most part of the world. Since thermometer-based observations began, the year 2016 was the warmest on record and 16th of the 17th hottest years on record occurred in this century.[1,2] The findings from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reveal that in the last decade, the frequency of extreme weather events, such as heat waves, floods, droughts, cyclones and wildfires has increased.[3] Scientific evidence indicates that the exposure to excessively high heat levels is already resulting in excess morbidity and mortality in the general population, particularly among the elderly.[4–7] In a recent study, it was estimated that around a third of the world's population actually faces deadly heatwaves and this percentage will grow to about 50% by 2100 even if greenhouse

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gas emissions are drastically reduced.[8] In particular, heat extremes have been shown to expose people to serious heat-related health risks including heat stroke, severe dehydration and exhaustion. Workers involved in moderate- or high-intensity outdoor activities or exposed to additional heat sources in the workplace during the warm season are especially prone to heat-related health problems.[9,10] In fact, physical work activities create intra-body heat production, which adds to the environmental heat stress, and the workplace accident risk is also affected.[11] Recent systematic reviews of epidemiological studies about heat and cold temperature effects on work-related injuries have been published, identifying categories of workers at risk and evaluating heterogeneity and sources of bias of reviewed studies.[12] Temperature extremes may lead to diminished occupational performance capacity and general performance degradation with a consequent increase of accidents and occupational injuries.[13]

In recognition of these effects, the International Labor Organization has recently issued a document that highlights the need for health programs and actions to preserve the health of workers who carry out heavy and moderate labor in very hot environments.[11] Such measures include low cost interventions such as assured access to drinking water in the occupational setting, increasing rest breaks, and the management of output targets. The document also stresses the need for a better assessment of the health consequences of global warming, as emerging analysis results can be the basis for effective national adaptation and mitigation policies.

The relationship between rising temperatures and the risk of heat-related occupational injury is among the aspects that require a more in-depth analysis. In fact, although the evidence reporting an association between working with high heat stress and work-related injury is growing, and several studies making use either of workers' compensation claim data,[14–20] or hospital discharge records,[21] or questionnaire surveys[22] have been completed, the extent of such association has not yet been clearly assessed. As part of HEAT-SHIELD, a project funded by the European Union under the Horizon 2020 Framework Programme for Research and Innovation, we conducted a meta-analysis of observational studies with the primary objective of summarizing the epidemiological evidence of the associations between rising heat due to climate change and occupational injury risk, particularly in sectors with outdoor workers (ie, agriculture and construction), that are especially put at risk in high or hot temperatures. A secondary objective was to identify occupational sectors at increased risk of heat stress.

2 | METHODS

2.1 | Search strategy and inclusion criteria

Building on the foundations of our previous work,[23] we conducted in PubMed an updated (from 01 January 2000 to 03 October 2018) version of a search strategy focused on traumatic injuries and acute death, applying a modified versions of the PICO scheme,[24] that is, using a search syntax comprising of three categories: (i) *Exposure*; (ii) *Setting*; (iii) *Health outcome*. When building the search syntax, for prompt identification of studies conducted in the occupational setting, the strings developed precisely for this purpose by Mattioli et al were used.[25]

The pre-specified search terms used are shown in Table 1. To complement the search in PubMed, the EMBASE database was consulted, using a more concise search strategy, given EMBASE characteristics, that is, the need for utilizing broader, not too-specific key terms, in order to increase the chance of capturing relevant studies: [('climate change'/exp OR 'climate change') AND worker* AND injur*].

The reason why the term "climate change" has been used as a research strategy in this study depends on the fact that most studies already published to investigate the effects of high temperatures on health justify such effects as a consequence of climate change, even if a detailed climatological analysis would require historical time-series of at least 20 years.[26] In particular, the difficulty to find very long historical health-related time-series makes it difficult, if not impossible, to carry out epidemiological investigations able to respect this criterion. Most studies linking workplace injuries with high temperatures make explicit reference to climate change to justify global warming. The results of these studies could be helpful to estimate future impacts of global warming (characterized by a rising frequency and intensity of heat wave and a general increase of exposure of workers to hot days), as well as to plan preventive interventions in the work¬place and to develop climate adaptation strategies.

A two-step selection process was applied: relevant studies were selected by screening first the titles and then the abstracts; if the information in titles or abstracts was not sufficient to decide on inclusion or exclusion of the study, the full-text was retrieved and evaluated. The study selection process was done twice, independently by two researchers (ML and AB), to ensure that the predefined selection criteria were met. Disagreements about eligibility were resolved through discussion between the two researchers (AB and ML). Information on the selected studies was extracted by one reviewer (ML) based on the following items: source (first author and year of publication), study design, year of publication, country/region

TABLE 1 Search strategy used to identify publications focused on traumatic injuries and acute death

#1	It identifies hazards/ exposures	("air temperature" OR "climate change" OR "climate variability" OR "global warming" OR heat OR "hot temperature" OR "heat wave*")
#2	It identifies the occupational setting	("occupational exposure"[MeSH Terms] OR "occupational risk"[TW] OR "occupational hazard"[TW] OR "Industry"[Mesh:noexp] OR "construction industry"[MeSH Terms] OR agriculture[MeSH Terms] OR "occupational group*" OR "work related"[All Fields] OR "working environment"[TW] OR worker*[TW])
#3	It identifies the outcomes	(injur* OR safety)
	Overall search strategy	(#1 AND #2 AND #3) NOT animal* (Filters activated: English, from 01.01.2000 to 03.10.2018)

considered, study population, mean age of study subjects, period of observation, heat-exposure index employed, and main findings. No additional studies were identified from hand-searching references and all full-texts of the included titles and abstracts could be retrieved. Complete articles examining the association between hot weather and work-related injuries were included in the meta-analysis when they complied with the following inclusion criteria:

- Articles published in peer reviewed journals;
- English language;
- Epidemiologic studies published from 01 January 2000 until 03 October 2018, with a case-crossover or time-series design;
- Studies involving humans (men or/and women);
- Studies focused on heat-related injuries among workers, with special attention to the construction and agricultural sectors;
- Studies with available meteorological data, with the following heat-exposure indexes: daily maximum and daily minimum temperatures; Wet Bulb Globe Temperature (WBGT) or other heat stress indices; heat wave classifications;
- Studies providing effect estimates with the corresponding measures of variability.

The exclusion criteria were:

- Experimental studies (eg, studies involving subjects performing exercise in climatic chambers), under controlled conditions of heat stress;
- Studies assessing the effects on subgroups whose exposure to heat is determined by industrial processes (eg, workers of foundries or glass mills) or by environmental conditions potentially not related to climate change (e.g., underground miners, firefighters), unless the unfavorable environmental conditions described were explicitly correlated to the heat conditions that climate change brings;
- Studies devoted solely to the analysis of the health effects of natural disasters (eg, Hurricane Katrina);
- Editorials, commentaries, letters to the editor and conference proceedings.

Case-crossover and time-series study designs have been increasingly used to analyze the association between acute health events and environmental exposures.[27,28] They match case and control days within a short interval of days or months (case-crossover) or use generalized additive models to estimate the total number of events on each day as a function of the exposure level and potential confounding variables (time-series).[29] Both time-series and case-crossover analyses allow adjustment for time-unvarying confounders (such as age) and confounding effects of trends and seasonality (eg, temperature, pressure, relative humidity), and are suitable methods in ecological studies.

2.2 | Risk of bias and quality assessment

The quality of the studies included in the meta-analysis was independently evaluated by the authors, based on the Navigation Guide methodology for systematic review.[30] Currently a fully reliable methodology for the assessment of the risk of bias in environmental studies is still lacking, but the Navigation Guide uses the best applicable methods. Two authors independently assessed the following domains: recruitment strategy, blinding, exposure assessment, outcome assessment, confounding, incomplete outcome data, selective reporting and conflict of interest. The quality of individual studies was rated based on fixed and unequivocal criteria in which the end result is one of the following possible statements about the risk of bias: "low," "probably low," "probably high," "high."

2.3 | Statistical analysis

The relative risks and the 95% confidence intervals (CI) of work-related injuries associated with the highest temperatures were obtained from each study. The main analysis included six studies (together and separately for time-series and case-crossover studies). Meta-analysis was carried out also for subgroups within studies based on the most relevant associations found in the studies concerning exposure to high temperatures: male gender, age <25 years, outdoor or indoor exposures, exposures in agriculture and construction sector.

2.4 | Evaluation of heterogeneity

The Q statistical test was used for assessing the heterogeneity of the results among the different studies, with degrees of freedom (df) equal to the number of studies minus one. The I^2 measure was used to quantify the heterogeneity between studies, as a measure of the percentage of the total variation that cannot be explained by chance.[31] In order to calculate the pooled estimate and its confidence intervals, we first used a fixed-effect model with the inverse variance weighting method. This results in a weighted average ($\bar{T}$) of the log-relative risks (T_i) of the individual studies where the weights (w_i) are given by the inverse of the study specific variance estimates ($1/S_i$). Confidence intervals were obtained by normal approximation. Under the fixed-effect model it is assumed that all studies are estimating the same effect size: it does not directly address between-study differences, in particular the possibility that studies' estimated parameters differ by more than chance alone. Because of this, an alternative random-effects model is preferred to the fixed-effects model in which the weights in the weighted average additionally incorporate a second component of variation that describes the differences in the studies' underlying parameters.[32] The observed variance is divided into within-studies and between-studies variances and then both parts are used when assigning the weights. The purpose will be to take account of both sources of imprecision. Thus the estimated pooled ($\bar{T}_{rand}$) can be obtained as weighted average where the inverse variance includes a term for between-study variance (τ^2). The amount of variation between the collected effect sizes is shown together with the pooled estimates by the forest plots. Small-study effects and publication bias were investigated using Begg funnel plots and Egger's test. Small-study effects are a common threat in systematic reviews and may indicate publication bias, which occurs when small primary studies are more likely to be reported (published) if their findings were positive. Their existence is often verified by visual inspection of the funnel plot, where for each included study of the meta-analysis, the estimate of the reported effect size is plotted against a measure of precision or sample size. The scatter of plots should reflect a funnel shape, if small-study effects do not exist. However, when small studies are predominately in one direction (usually the direction of larger effect sizes) asymmetry will result.

All statistical tests were two sided, and a *p*-value < 0.05 was considered statistically significant. All analyses were performed with StataCorp. 2013 (Stata Statistical Software: Release 13 College Station, TX).

3 | RESULTS

The search strategy resulted in the review and selection of 406 studies. Based on titles and abstracts, the full-texts of 87 potentially relevant articles were retrieved and reviewed. This resulted in 12 studies to be potentially included in the meta-analysis. Of these, four were further excluded: two on account of overlapping dataset/period/region;[15,18] one study adopted a study design other than time-series or case-crossover analysis (ie, a cross-sectional study[33]), and in the remaining one the heat exposure metric adopted did not allow direct comparisons.[22] In total, three case-crossover studies[17,34,35] and five time-series studies[14,19,20,36,37] were finally selected for the meta-analysis (Figure 1). Two studies were specific to exposures in agriculture; therefore, their estimates were used only in the subgroup meta-analysis of agriculture.[17,36]

The quality assessment for the included studies is summarized in Table 2. The domain of blinding was removed, as not applicable to the reviewed studies. Seven studies had a probably low risk of bias for recruitment strategy, because the injuries information generally come from structured databases. Four studies had a probably high risk of bias in exposure assessment due to the lack of precision of meteorological data. Six studies had a low risk of bias in outcome assessment, because studies have used routine administrative data, assumed to have a high degree of completeness. Confounding was identified at high risk of bias in four studies, because multiple important potential confounders were not evaluated. Four studies had a probably high risk of bias in incomplete outcome data because there was insufficient evidence that such data were adequately addressed. For all studies we assigned a low

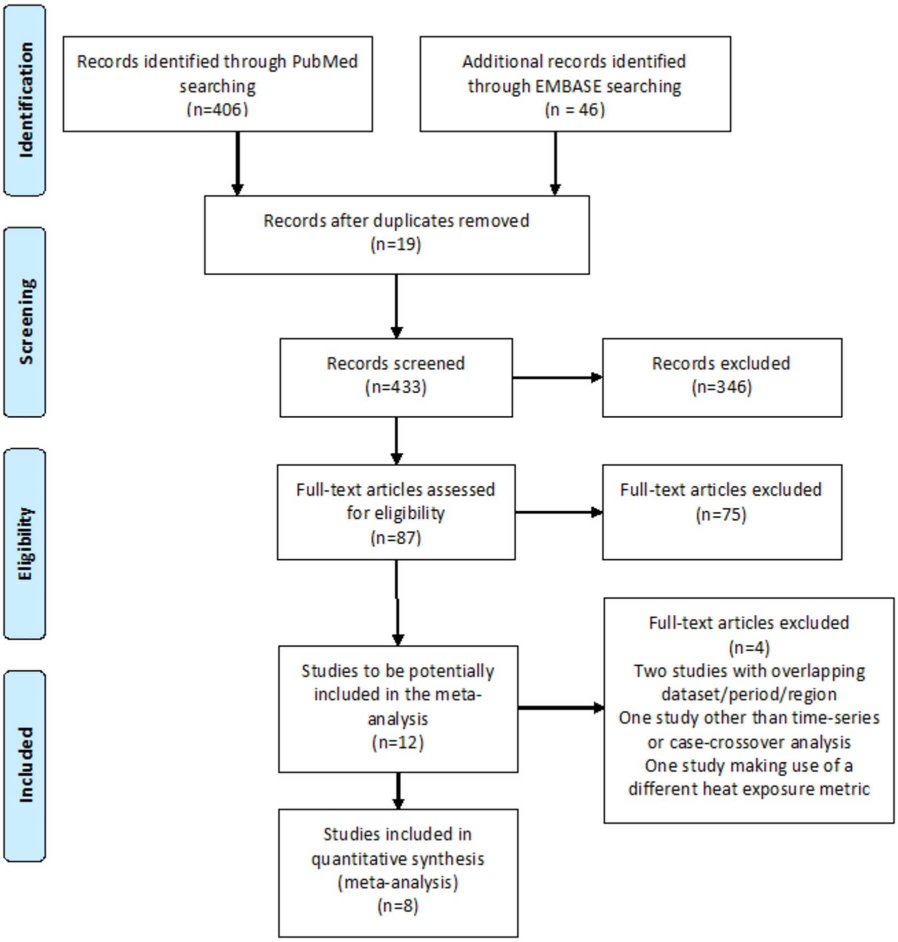

FIGURE 1 Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) flow diagram for inclusion of studies in the meta-analysis [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Assessment of quality of the studies included in meta-analysis: review authors' rates about each domain of risk of bias for each included study

Domains of risk of bias	Time-series studies: Adam-Poupart et al.[14]	Garzon-Villalba et al.[20]	Xiang et al.[19]	Riccò[36]	Martinez-Solanas et al.[37]	Case-crossover studies: McInnes et al.[34]	Spector et al.[17]	Sheng et al.[35]
Recruitment strategy	PL	PL	PL	PL	PL	PL	PL	PH
Exposure assessment	PH	PL	PH	PH	PL	PL	PL	PH
Outcome assessment	L	H	L	L	L	L	L	PL
Confounding	H	H	H	H	PL	PL	PL	PL
Incomplete outcome data	PL	PH	PL	PH	PL	PH	PL	PH
Selective reporting	L	L	L	L	L	L	L	L
Conflict of interest	L	L	PL	PL	L	L	L	L

L, Low risk; PL, Probably low risk; PH, Probably high risk; H, High risk.

risk of bias in selective reporting. Most studies had a low risk of bias in conflict of interest. As for the study by Riccò,[36] an additional bias was considered, regarding the incompleteness of data about the total number of subjects employed in agricultural activities at the time of injury occurrence: it is possible that the study assessment underestimated the actual rates of occupational injuries during the hottest days, while also overestimating them when workforce significantly increases, such as during wine harvesting and fruit picking. (The main characteristics of the studies included in the meta-analysis are reported in Table 3.)

Given the different methods of temperature measure in each study included in the meta-analysis, the association between occupational injuries and the highest temperature registered in the study period was selected for the analysis. In three studies, the chosen risk estimate was per 1°C increase in daily maximum temperature (32 – 37°C).[14,19,35] In the study of Garzon-Villalba et al, the association of temperature with occupational injury risk was estimated considering the possible cumulative effect of maximum Wet Bulb Globe Temperature (WBGTmax), with WBGTmax referenced to 28°C-WBGT.[20] With regard to other studies, the risk estimate was chosen for the temperature comprised within the 95th or 99th percentile of daily maximum temperatures (threshold ranging from 35.5 to 37.1°C)[34,36,37] with the exception of the study by Spector et al, where the daily maximum Humidex of 34°C or greater was used.[17] Compensation for occupational injuries that occurred in the warmest months (generally comprised between May and September, or October-March depending on the geographical location) were used in most studies (except when other databases of occupational injuries were used), in periods of study ranging between 1994 and 2014.

First, separate group analyses were performed for time-series studies and case-crossover studies. The combined effect of both time-series and case-crossover studies was then estimated. In these analyses, the two studies specific of agriculture were not included.[17,36] Heterogeneity was tested for the groups of case-crossover and time-series studies separately, and then for both groups combined (Table 4a). Except for the group of case-crossover studies, statistical significance was observed ($p < 0.001$): as a consequence, the hypothesis of an identical effect for all the studies was rejected, and to take into account this lack of homogeneity, the analyses have been performed with a random effects model. The absence of statistical significance in the Q-test for case-crossover studies ($p = 0.522$) complied with the application of a fixed-effects model. Successively heterogeneity was tested for the pooled risk estimates by male gender, age less than 25 years, outdoor and indoor exposures, agriculture and construction sector, with a $p < 0.001$ requesting a random effects model (Table 4b). The pooled relative risk for occupational injuries was estimated at 1.002 (95%CI: 0.998-1.005) for the time-series studies, at 1.014 (95%CI: 1.012-1.017) for the case crossover studies, and at 1.005 (95%CI: 1.001-1009) for the six studies combined (Table 4a). Subgroup pooled estimates showed increased relative risks for male gender, age less than 25 years and agriculture (although not statistically significant), whereas no association was found for indoor and outdoor working environments and the construction sector (Table 4b). Figures 2 and 3 show the forest plots with the pooled estimate for the six studies combined and for the subgroups of exposures investigated. By symmetric Begg funnel plots and non-significant Egger's tests ($p = 0.246$ for all studies and $p = 0.646$ for agriculture studies), no small-study effects and absence of publication bias were detected (Figures 4 and 5). In the present meta-analysis, studies characterized by a higher variance are more widespread with respect to those showing a greater precision (lower standard error) that tended to cluster closely to the summary estimate (top of the funnel plot). In Figure 4, three studies have larger sizes (weights from 27.24% to 31.89%) than the other three (weights from 0.03% to 8.25%). In Figure 5, results from small studies scatter widely at the bottom of the graph (weights from 1.96% to 3.26%) and only one (weight: 92.66%) at the top. Egger's test is a formal test to assess the presence of funnel plot asymmetry: it typically estimates the association between the reported effect size and their standard error, the total sample size, or the inverse of the total sample size.

4 | DISCUSSION

The relationship between high temperatures, heat waves and population health has been well documented. Epidemiological

TABLE 3 Studies selected conducting the search strategy in PubMed and EMBASE

Reference	Study type	Location and population	Output	Period of study	Period of heat exposure	Heat exposure measurement	Main findings
Adam-Poupart et al.[14]	time-series	Canada; 374,078 work-related injury compensations	daily counts of compensations	2003-2010	May-September	1°C increase in daily maximum temperatures	Increased risk of daily work-related injury compensations per 1°C increase (IRR: 1.002; 95%CI: 1.002-1.003). Higher risk observed for men (IRR: 1.003; 95% CI: 1.002-1.005), age <25 years (IRR: 1.008; 95%CI: 1.005-1.010), some industrial sectors with both indoor (IRR: 1.003; 95%CI: 1.000-1.005) and outdoor activities (IRR: 1.004; 95%CI: 1.001-1.006).
McInnes et al.[34]	case-crossover	Australia; 46,288 claims	work-related injury	2002-2012	November-March	≥60th-95th percentiles of maximum and minimum daily temperature distribution (2 or 3 consecutive days)	Increased risk of work-related injury for workers exposed to 2 or 3 consecutive days of hot weather, with more pronounced effect as temperatures and duration of exposure increase (OR: 1.09; 95%CI: 0.87-1.36 at 95th percentile of maximum daily temperature for three consecutive days).
Xiang et al.[19]	time-series	South Australia; 252,183 workers' injury claims	work-related injury	2001-2010	October-March	daily maximum temperature (T_{max})	Increased risk of occupational injuries not above (IRR: 0.986; 95%CI: 0.975-0.998) but below the threshold temperature (IRR: 1.002; 95%CI: 1.001-1.004), particularly for men (IRR: 1.004, 95%CI: 1.002-1.006), agriculture, forestry and fishing (IRR: 1.007; 95%CI: 1.001-1.013) and construction sector (IRR: 1.006; 95%CI: 1.002-1.011).
Garzon-Villalba et al.[20]	time-series	USA; 20,033 occupational injuries	exertional heat illness and acute injury	2010-2011	May-March	Max WBGT (Wet bulb temperature)	Higher risk of exertional heat illness (RR: 1.58; 95%CI: 1.52-1.64) and acute injuries (RR: 1.13; 95%CI: 1.09-1.17) with increasing Wet Bulb Globe Temperature (WBGT).
Spector et al.[17]	case-crossover	USA (Washington State); 12,213 agriculture injury claims	occupational injury agriculture	2000-2012	May-October	Max daily Humidex	Increased risk of heat-related traumatic injuries for agricultural workers laboring in warm conditions (OR: 1.08; 95%CI: 0.99-1.18 at maximum daily Humidex).
Sheng et al.[35]	case-crossover	China; 5,418 worker's compensation claims	work-related injury	2011-2012	May-October	1°C increase in daily maximum and minimum temperature	Increase in daily injury claims for 1°C increase in maximum temperature (RR: 1.014, 95%CI: 1.012-1.017), particularly for men (RR: 1.014; 95%CI: 1.011-1.016) and middle-aged workers (RR: 1.021; 95%CI: 1.017-1.024), small (RR: 1.014; 95%CI: 1.011-1.017) and medium-sized enterprises (RR: 1.017; 95%CI: 1.013-1.022), manufacturing sector (RR: 1.019; 95%CI: 1.015-1.022) and finance, property and business services (RR: 1.014; 95%CI: 1.009-1.019).
Riccò[36]	time-series	AP Trento (Italy); 7,325 worker's compensation claims	work-related injury	2000-2013	May-September	daily maximum and average temperature	Peak of work-related injuries occurred on days characterized by severe thermal conditions, and in particular during heat waves. Highest risk at 95th percentile of maximum daily temperature (OR: 1.144; 95%CI: 1.029-1.272).
Martínez-Solanas et al.[37]	time-series	Spain; 15,992,310 occupational injuries	work-related injury	1994-2013	May-September	daily maximum and minimum temperature	Attributable occupational injuries (%): 2.40 (95%CI: 2.09-2.68); extreme heat increased the risk of occupational injuries (PD: 9; 95%CI: 8-11). Higher risk in men (PD: 9; 95% CI: 7-12), younger workers (PD: 11; 95%CI: 8-14) and agriculture (PD: 29; 95%CI: 23-36).

TABLE 4 Meta-analyses results for selected studies (exposure to the highest temperature) by study types (**A**) and subgroups of exposed (**B**)

	N estimates/N studies	Summary estimate (95%CI)	Q Statistic (df, *p*-value)	I^2 (%)
A				
Study types				
Time-series studies only	4/4	1.002 (0.998-1.003)	53.01 (3, <0.05)	94.3
Case-crossover studies only	2/2	1.014 (1.011-1.017)	0.41 (1, 0.522)	0.00
All selected studies*	6/6	1.005 (1.001-1.009)	119.03 (5, <0.05)	95.8
B				
Subgroups				
Men	4/4	1.004 (0.993-1.014)	68.74 (3, <0.05)	95.6
Age (<25 yrs)	4/4	1.004 (0.997-1.011)	12.95 (3, <0.05)	76.8
Indoor	3/3	0.997 (0.983-1.011)	6.38 (2, <0.05)	68.6
Outdoor	3/3	0.985 (0.949-1.022)	43.71 (2, <0.05)	95.4
Agriculture**	4/4	1.029 (0.956-1.107)	11.52 (3, <0.05)	74
Construction	2/2	0.979 (0.932-1.028)	26.90 (1, <0.05)	96.3

*Egger's test (*p*-value): 0.246.
**Egger's test (*p*-value): 0.646

evidence suggests that extremely hot weather contributes to excess morbidity and mortality, particularly among the elderly and patients on pharmacologic treatment for non-communicable diseases.[38,39] The interest in the impact of heat-related events on workers' health and safety has recently increased. Studies have demonstrated that intense and prolonged occupational exposure to elevated temperatures has been associated with health effects, such as dehydration and spasms, increased fatigue, and reduced productivity.[40–42] The increased risk of workplace injuries may be the consequence of sweaty palms, fogged-up safety glasses, dizziness, and reduced cognitive performance.[43] At present, however, the published epidemiological studies on the association between occupational injuries and hot weather are scarce, as different methods have been applied.[12]

In the present analysis, the estimated association between high temperature exposure and occupational injuries shows a positive relationship by time-series studies, case-crossover studies and by combined studies analysis. To our knowledge, meta-analyses of studies comparing results from both time-series and case-crossover analysis are not available with respect to heat-related work injuries. A higher effect size was estimated from the case-crossover studies than the time-series studies (the results were statistically significant in the first group). However, due to the low number of studies used in the meta-analysis, these findings do not allow a comparison of the two designs of study.

We observed that young workers, male workers and workers engaged in agriculture were at risk of occupational injuries with high temperatures, although the estimates were not statistically significant.

The increase of occupational injuries observed for men possibly reflects gender differences in the industrial sector of employment. Men more likely work in high-risk occupations, such as agriculture, forestry, fishing, mining and oil and gas extraction and construction.[44] The increased risk for young workers (less than 25 years old) could be

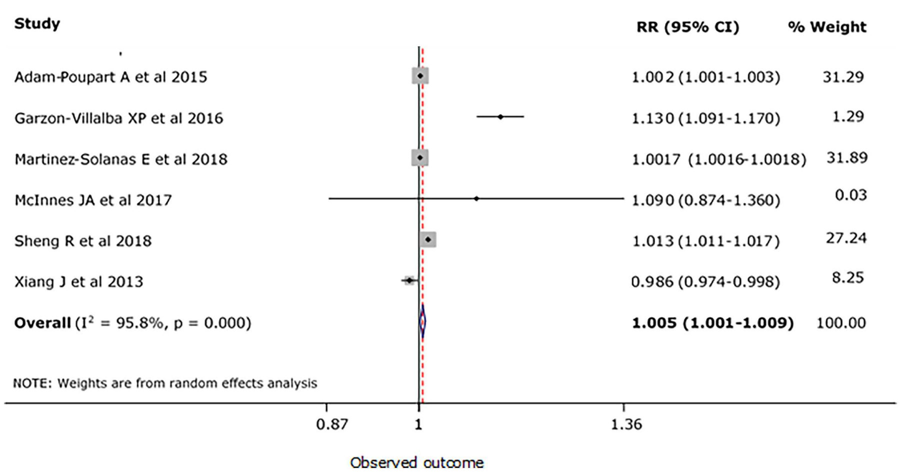

FIGURE 2 Forest plot of study-specific RRs and RR_{pooled} (95%CIs), stratified by the time-series and case-crossover studies. The size of the squares reflects the statistical weight of the study in the meta-analyses [Color figure can be viewed at wileyonlinelibrary.com]

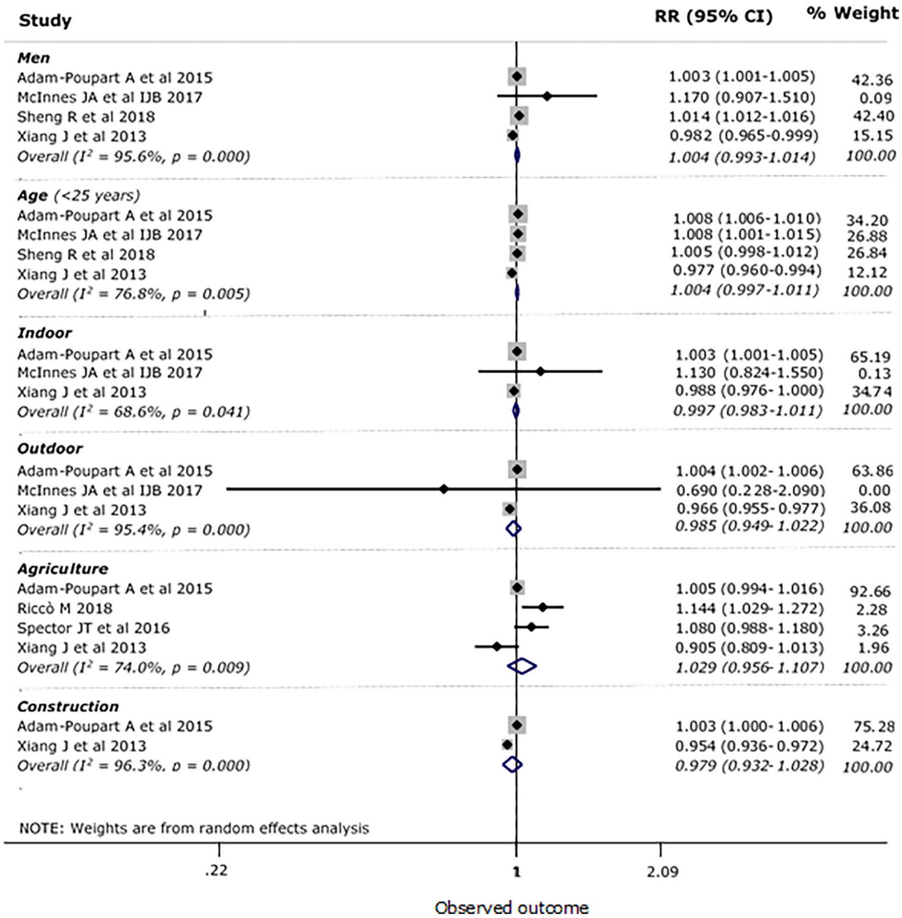

FIGURE 3 Forest plots of study-specific RRs and RR_{pooled} (95%CIs), stratified by subgroups of exposure (men, age <25 years, Indoor, Outdoor, Agriculture, Construction). The size of the squares reflects the statistical weight of the study in the meta-analyses

caused by the more arduous tasks and physical activity experienced by workers in this age group. Moreover, they often receive less safety training, or have fewer skills than older workers. Some studies also observed that young workers may be less likely to recognize the risk of heat exposure and show low compliance with preventive measures.[45]

No differences in risk were found between indoor and outdoor exposures. This may be related to the fact that data available from the collected studies do not recognize indoor versus outdoor injuries. Moreover, the studies often lack information on the availability of air conditioning in sectors with mainly indoor work. Nevertheless, some

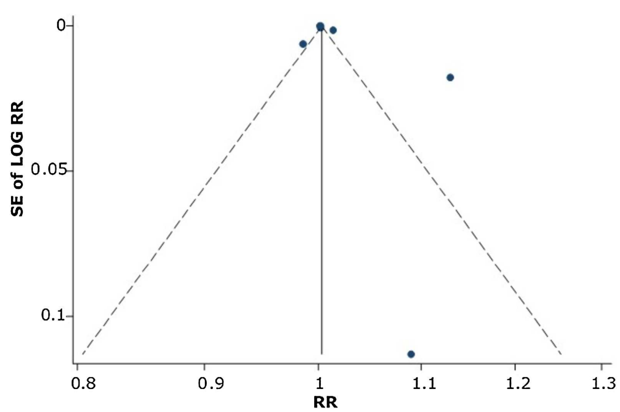

FIGURE 4 Funnel plot of studies included in the meta-analysis for the risk of occupational injuries associated with exposure to high temperatures

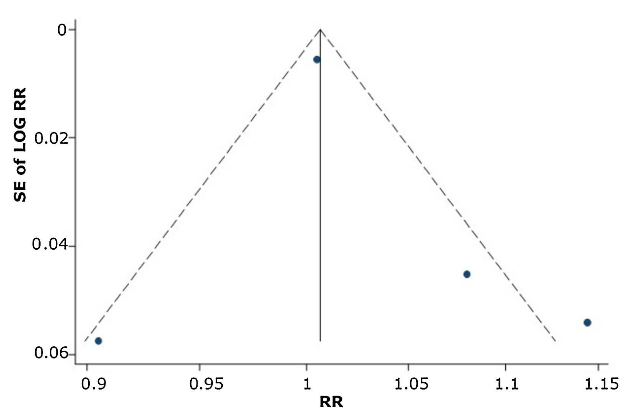

FIGURE 5 Funnel plot of studies included in the meta-analysis for the risk of occupational injuries associated with exposure in agriculture

statistically significant risks for sectors with predominantly indoor activities were observed, suggesting either an additive effect of outdoor heat to the high internal temperature deriving from heat-generating industrial processes, or intense physical work with the absence of heat-relieving devices, or missing protective policies during hot waves.[14] The impact of high temperatures on indoors working activities, with implications for the performance and productivity of workers, deserves further investigation.

We found an excess risk, although not statistically significant, in agriculture. Such workers are usually exposed to outdoor extreme heat for long periods, often entailing the use of personal protective equipment (PPE). Since the wearing of PPE enhances physical stress and limits heat dispersion from the body, the risk for heat-related illness increases. This may lead to a decrease in their use and further amplifies the risk of injuries, frequently in association with handling of chemicals (eg, pesticides and fertilizers).[36]

We found no excess of risk in the construction sector. A reduction of accidents could be attributed both to behavioral changes of workers, who may adapt their work intensity to reduce excessive effort,[16] and to preventive measures implemented by the employers. Moreover, a lower number of injuries has been reported during heat wave periods compared to normal working days in summer months, suggesting the existence of control measures in construction sites to prevent accidents during heat waves.[17]

This study has several limitations. First is the limited number of epidemiological studies available on this topic. However, it is necessary to consider that the works selected for this meta-analysis are all relatively recent and carried out in the last 15 years. Heat-related injury studies often considered a few years, mainly because details of this information are only recently available. Moreover, the results from each of the included studies varied in population size, temperature measurements, work-related injuries reckoning and consequently size estimate. In addition, different statistical approaches were often used, thus making the application of a meta-analysis to summarize the epidemiological evidences more complex.

The differences in each study region or city should be considered in the interpretation of the results as well. Population-level studies investigating the health impact of heat suggested that effects vary geographically, accounting for the acclimatization, sensitivity and adaptive capacity of exposed populations.[46] Furthermore, the exposure and outcome measures used in the studies are not always aligned.

The relationships between heat and working injuries have been studied by using different thermal stress indicators, from simple air temperature to more appropriate heat stress indices. The use of temperature and humidity as indicators of heat stress often does not consider the influence of other factors that could play an important role. The heat stress index most widely employed in the occupational studies is the Wet Bulb Globe Temperature (WBGT), which takes into account air temperature, humidity, solar radiation and wind speed in a single index. However, this index is not regularly measured, and data necessary to estimate it are not always available. A comparative approach to define hot weather using temperature percentiles was used by some authors, identifying the 95th maximum daily temperature percentile as characterizing extreme heat. Evidence suggests that impacts of hot weather in occupational settings may not be clear at extreme temperatures.[17,19,21] Exposure misclassification can also derive from missing information about actual workplace or residential temperatures to which cases were exposed.

Moreover, the effect of temperatures is expected to be underestimated in a large number of workers who mostly work outdoors and are employed in sectors well-known for under-reporting injuries, such as agriculture, forestry, fishing and construction.[17] The role of personal risk factors such as alcohol consumption, chronic diseases, use of drugs is not known, and is another concern about heat-related disorders, like acute injuries and physical exertion heat injuries. Lastly, with regard to the measure of outcome, the use of compensation claim data as a source of work-related injuries likely underestimates the true number of injury cases, as not all workers entitled for compensation will submit a claim, and not all claims for injury will be eligible for compensation.

The risk of bias in confounding was a critical point of half of the included studies, and this suggests to improve in the future the inclusion of all potential confounding factors for this kind of ecological studies. Anyway, most of the studies were assessed to have an average good methodological quality, and supported the validity of our pooled analyses. Further studies are needed using longer time-series of working injuries, stratified for different work efforts and using more appropriate thermal stress indicators for workers, such as the WBGT (the international standard for occupational purposes [ISO 7243, 2017]).[47] Future studies using adequate statistical approaches, such as case-cross over and time-series design, are strongly desirable.

In the interim, it is crucial to start implementing effective interventions to prevent the occupational health impacts of heat stress, especially considering that, for the International Labor Organization,[11] such measures often include low-cost and easy to implement measures such as ensuring easy access to drinking water in the workplace and scheduled rest breaks in cool locations. One of the specific objectives of the HEAT-SHIELD Project is the formulation of heat impact prevention guidelines, based both on scientific evidence and on feedback from direct and public consultation, including the involvement of stakeholders from strategic industries, in order to promote workers' health and support their productivity. Current guidelines and heat management systems to counteract increasing heat exposure in occupational settings need to be implemented in at-risk regions, including the Mediterranean countries, which constitute one of the regions in the world most vulnerable to the impacts of climate change.

Subsequently, a series of state-of-the-art innovative interventions, which will include a weather-based warning system with online open access service to help industry and society anticipate threats to workers' health and to help disseminate formulated recommendations, will be developed. The ultimate aim of the Project is to create a sustainable inter-sector framework that will promote health and productivity in the EU and beyond in the context of the serious environmental challenge represented by global warming.

AUTHORS' CONTRIBUTIONS

Alessandra Binazzi (ABi) performed the meta-analysis of retrieved studies, interpreted the data and drafted the paper. Miriam Levi (ML) performed the systematic examination of the literature, provided critical assessment of published studies, interpreted the data and contributed to draft the paper. Michela Bonafede (MBo) and Marcella Bugani (MBu) contributed to perform the meta-analysis, interpret the data and to draft the paper. Alessandro Messeri (AM) and Marco Morabito (MM) interpreted the data and contributed to draft the paper. Alberto Baldasseroni (AB) and Alessandro Marinaccio (AMa) conceived and supervised the study, interpreted the data and critically revised the manuscript for important intellectual content. All authors approved the final version of the manuscript for publication and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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ETHICS APPROVAL AND INFORMED CONSENT

Not applicable, since the work was a meta-analysis of observational studies.

DISCLOSURE (AUTHORS)

The authors report no conflicts of interest.

DISCLOSURE BY AJIM EDITOR OF RECORD

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DISCLAIMER

Responsibility for the information and views set out in this study lies entirely with the authors. The European Commission is not responsible for any use that may be made of the information contained herein.

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