Indonesian Journal of Global Health Research
Volume 9 Number 1, Februari 2027
e-ISSN 2715-1972; p-ISSN 2714-9749
https://jurnal2.globalhealthsciencegroup.com/index.php/IJGHR

OCCUPATIONAL HEAT EXPOSURE AND PHYSIOLOGICAL RESPONSES AMONG OUTDOOR WORKERS: A SYSTEMATIC REVIEW

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ABSTRACT
Alterations in workers physiological responses while working in heat-exposed environments may lead to the manifestation of various health disorders. This systematic review aimed to synthesize evidence on workers physiological responses to occupational heat exposure and assess potential sex-related differences. Following the PRISMA guidelines, this systematic review aimed to synthesize workers physiological responses to occupational heat exposure and evaluate evidence of sex-related differences. The review applied the Population Concept Context framework. Scopus was searched for final-stage, peer-reviewed journal articles published in English between 2010 and 2026. Eligible studies involved adult outdoor workers exposed to occupational heat, reported at least one physiological or renal outcome, and used observational or interventional designs. Studies were grouped according to physiological outcome domain and type of sex-specific evidence. Fifteen studies involving 7,725 workers were included. Occupational heat exposure was most consistently associated with thermoregulatory strain, followed by dehydration and cardiovascular responses. Renal abnormalities were also frequently reported. Evidence of sex-related differences was limited and inconsistent, with findings strongly influenced by workload, job type, hydration access, sanitation, and employment conditions. Women showed greater cardiovascular and physiological strain in some settings and faced additional dehydration risk due to inadequate sanitation, although the evidence remained limited. Current evidence does not establish that either sex is consistently more physiologically susceptible to occupational heat. Multicomponent heat-management strategies and better-designed sex-disaggregated prospective studies are needed.

Keywords: occupational heat exposure; outdoor workers; physiological responses; sex-related differences

First Received	Revised	Accepted
03 August 2026	11 September 2026	28 October 2026
Final Proof Received		**Published**
15 November 2026		01 February 2027

How to cite (in APA style)
Putri, N. A., Denny, H. M., Rahfiludin, M. Z., & Lestantyo, D. (2026). Occupational Heat Exposure and Physiological Responses among Outdoor Workers: A Systematic Review. *Indonesian Journal of Global Health Research*, *9*(1), 195–208. https://doi.org/10.37287/ijghr.v9i1.2528.

INTRODUCTION

Occupational heat exposure is an increasingly important occupational health challenge as climate warming expands hazardous working conditions. Outdoor workers are especially vulnerable because direct solar radiation, humidity, physical workload, and limited workplace controls act simultaneously(Habibi, Heydari, et al., 2024; Nowrouzi-Kia et al., 2026). Field studies have documented substantial heat strain and dehydration among agricultural, construction, mining, and other outdoor workforces (Boonruksa et al., 2020; Hunt et al., 2014; Mac et al., 2019). Restricted access to rest, shade, cooling, and self-pacing may further increase physiological strain during hot work(Ioannou et al., 2021). The body responds to occupational heat through interconnected thermoregulatory, cardiovascular, hydration, and renal mechanisms. Sweating and increased skin

blood flow support heat dissipation, while heart rate rises to maintain circulation during physical work (Boonruksa et al., 2020; Ioannou et al., 2021). Prolonged sweating without adequate fluid replacement reduces hydration and intensifies cardiovascular strain (Hunt et al., 2014; Mac et al., 2019). When these mechanisms become insufficient, workers may develop hyperthermia, dehydration, altered kidney function, and renal-injury biomarkers (Butler-Dawson et al., 2024; Chicas et al., 2023).

Existing evidence shows that occupational heat exposure produces multisystem physiological strain across agriculture, construction, mining, and other outdoor occupations (Alele et al., 2020; Habibi, Razmjouei, et al., 2024; Ioannou et al., 2021). Reported effects include higher core temperature, heart rate, physiological strain, dehydration, and changes in renal biomarkers (Al-Bouwarthan et al., 2020; Boonruksa et al., 2020; Butler-Dawson et al., 2024). Recent reviews also show that recommendations for secondary and tertiary prevention remain less developed than primary prevention measures(Edgerly et al., 2025). The magnitude of these responses varies with age, body characteristics, acclimatization, workload, clothing, humidity, hydration access, sanitation, migration, and work organization (Habibi, Razmjouei, et al., 2024; Isaac et al., 2025). Available findings also suggest that sex-related responses are context-dependent rather than uniformly greater among either female or male workers (Mac et al., 2019; Renberg et al., 2022).

Despite this progress, sex-related differences remain insufficiently understood because many studies use single-sex or sex-imbalanced samples and report pooled physiological outcomes. Existing comparisons also rarely separate biological sex from workload, job assignment, clothing, exposure intensity, hydration, sanitation, and access to preventive resources (Mac et al., 2019; Renberg et al., 2022). To address this gap, the present review distinguishes direct within-study comparisons from limited, indirect, contextual, and non-comparative evidence. Accordingly, it synthesizes thermoregulatory, cardiovascular, hydration, and renal responses across female-only, male-only or male-predominant, and mixed-sex outdoor-worker populations. This systematic review aimed to synthesize evidence on workers physiological responses to occupational heat exposure and assess potential sex-related differences.

METHOD

This study relied on a systematic review of the published scientific literature on physiological responoses among outdoor workers exposed to occupational heat. This review was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement(Page et al., 2021). Scopus was used as the principal bibliograpic database to identify eligible studies. The review question was structured using the Population–Concept–Context (PCC) framework. The population comprised adult workers. The concept included occupational heat exposure and physiological responses, encompassing thermoregulatory, cardiovascular, hydration, and renal function or kidney injury outcomes, as well as evidence of sex-related differences in these responses. The context comprised outdoor occupational heat-exposure settings, including agriculture, construction, mining, and other field-based occupations.

Studies were eligible if they were primary empirical studies involving adult workers exposed to occupational heat; outdoor working environments; studies reporting at least one thermoregulatory, cardiovascular, hydration, or renal response; and also observational and interventional designs. Studies involving population as female-only, male-only or male-predominant, or mixed-sex worker were included. Reporting participant sex was required, however, the reporting of sex as a sample characteristic alone was not considered evidence of a sex-related difference. Studies were excluded if they involved non-worker populations, did not assess occupational heat exposure, reported only environmental heat or subjective thermal comfort without physiological outcomes, or were reviews, editorials, commentaries, conference abstracts without complete data, animal studies, or in vitro

studies. Only final, peer-reviewed articles published in English were included. For the synthesis, studies were grouped according to physiological outcome domain and type of sex-specific evidence.

The search strategy combined terms representing occupational heat exposure, worker populations, and physiological or renal responses. Synonyms within each concept were connected using the Boolean operator "OR", and the three concept groups were combined using "AND". Terms identifying systematic reviews, meta-analyses, and bibliometric studies were excluded using "NOT". The search was applied to the title, abstract, and keyword fields in Scopus. The complete search expression was: ("occupational heat stress" OR "occupational heat exposure" OR "workplace heat exposure" OR "heat strain") AND ("outdoor worker" OR occupational worker) AND ("physiological response" OR "heat strain" OR "core body temperature" OR "hydration status" OR "renal function" OR creatinine OR BUN OR eGFR OR NGAL OR KIM-1) NOT ("systematic review" OR "systematic literature review" OR "meta-analysis" OR "meta analysis" OR "bibliometric"). The search was limited to final-stage journal articles published in English. Years 2010-2026 and no restriction was applied according to open-access status.

RESULT

The Scopus search identified 120 records, all of which were screened after no duplicates were detected. Ninety-one records were excluded during title and abstract screening. Of 29 reports sought for retrieval, three were unavailable, leaving 26 full-text articles for eligibility assessment. Eleven articles were excluded because of ineligible physiological outcomes or insufficient sex-related evidence. Consequently, 15 studies were included in the review (Fig. 1). Studies involving both indoor and outdoor populations were retained only when data for outdoor workers were reported separately or could be clearly extracted. Only findings relating to outdoor workers were included in the present synthesis.

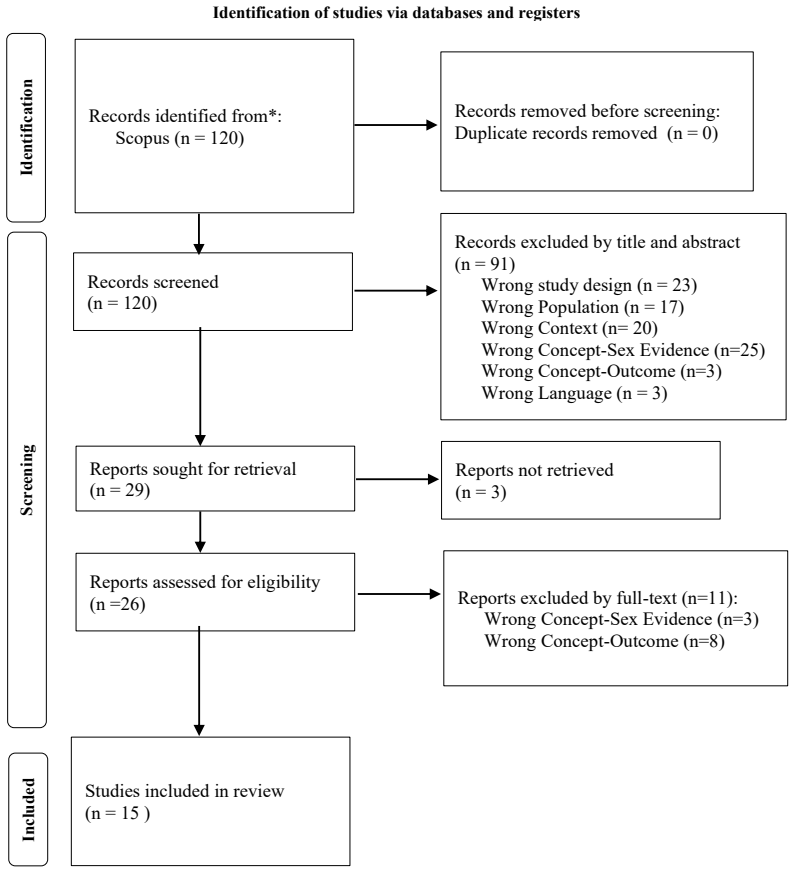


Figure 1. Review process flow chart illustrating the study selection results, following the PRISMA guidelines

The 15 included studies comprised 7,725 outdoor workers. Seven studies were conducted in India, three in Nicaragua, and one each in Kenya, Sri Lanka, Indonesia, the United States, and Hong Kong. Eight studies used cross-sectional designs, three were field studies, two were cohort studies, one was experimental, and one combined a cohort design with an occupational intervention. The study populations included farmers, agricultural labourers, sugarcane workers, construction workers, brickmaking and kiln workers, salt-pan workers, fishers, tea-plantation workers, and other outdoor informal workers. Sample sizes ranged from 48 Kenyan subsistence farmers to 1,136 Indian workers. For studies involving broader occupational populations, only outdoor-worker subsets were included in the synthesis. The main characteristics of the included studies are presented in Table 1.

Table 1.
Characteristics of the included studies reporting physiological responses to occupational heat exposure

Study	Country	Design	Worker population and sample	Occupational heat exposure	Physiological outcomes	Principal findings
(Kwaro et al., 2025)	Kenya	Field study	Subsistence farmers; n = 48	Outdoor agricultural work involving solar and metabolic heat exposure	Core body temperature, heart rate, physiological strain index	Outdoor WBGT was positively associated with physiological strain. Women had higher physiological strain index and peak heart rate than men despite similar measured activity levels.
(De Silva et al., 2022)	Sri Lanka	Cross-Sectional	Fishers, paddy and sugarcane farmers, and tea-plantation workers; n = 475	Outdoor solar exposure for approximately 4.1–8.8 hours per day	Serum creatinine, cystatin C, BUN, uric acid, eGFR, and urinary albumin-to-creatinine ratio	The occupational group with the highest measured heat exposure did not have the highest CKDu prevalence, indicating that occupational heat alone did not explain differences in kidney outcomes.
(Biswas et al., 2025)	India	Cross-Sectional	Farmers, construction labourers, and other workers; n = 1,136	Outdoor heat exposure for approximately six hours per day, frequently at ambient temperatures above 40°C	Hydration indicators, heat-shock proteins, eGFR, ACR, and renal indicators	Farmers showed substantial dehydration, elevated heat-shock proteins, and frequent heat-stress nephropathy. Recurrent dehydration and heat exposure were associated with tubulointerstitial kidney damage.
(Masuda et al., 2019)	Indonesia	Experimental	Rural subsistence workers; n = 361	Moderate harvesting activity in forested and deforested environments	Estimated core temperature, heart rate, and oral temperature	Work in deforested areas produced greater heat exposure and poorer cognitive performance. The adverse cognitive effect was more apparent among men and during assessments conducted after midday.
(Sankar et al., 2026)	India	Cross-Sectional	Local and migrant informal workers; n = 334	Outdoor agriculture, construction, brick-kiln, and stone work	Core temperature, heart rate, blood pressure, sweat rate, and urine-specific gravity	Migrant workers had a 3.2-fold higher dehydration risk and more frequent core-temperature increases exceeding 1°C than local

Study	Country	Design	Worker population and sample	Occupational heat exposure	Physiological outcomes	Principal findings
						workers.
(Venugopal et al., 2021)	India	Cross-Sectional	Outdoor unorganized workers (subset); n = 1053	Outdoor agriculture, construction, kilns, salt pans; avg. WBGT 29.1°C	CBT, SwR, USG, sCr, Egfr	Outdoor workers had 90.3% HRI prevalence and 11.4 times higher odds of productivity loss; females showed higher sensitivity to heat symptoms.
(Moyce et al., 2017)	United States	Field study	Agricultural field workers; n = 283	Outdoor work for at least six hours per day under high ambient temperatures	Core temperature, heart rate, body-mass change, serum creatinine, and acute kidney injury	Acute kidney injury occurred in 12.3% of workers after one shift. High physiological strain was associated with AKI among men, whereas body-mass loss was not directly associated with AKI.
(Laws et al., 2016)	Nicaragua	Cohort	Sugarcane workers in seven occupational groups; n = 284	Strenuous agricultural work under high ambient heat	NGAL, IL-18, NAG, albumin, serum creatinine, eGFR, and hydration indicators	Kidney-injury biomarkers increased during the harvest, particularly among cane cutters and irrigation workers. Electrolyte-solution intake was associated with more favourable biomarker profiles.
(Hansson et al., 2025)	Nicaragua	Cohort/ Intervention	Sugarcane cutters and field-support workers; n = 1,044	Strenuous outdoor work with progressively enhanced rest, shade, hydration, and hygiene controls	Serum creatinine, eGFR, CRP, and leukocyturia	A structured workplace intervention reduced acute kidney injury and inflammatory indicators, particularly among employees with the highest workloads.
(Venugopal et al., 2016)	India	Cross-Sectional	Brick and agricultural workers (outdoor subset); n = 225	Outdoor fields and kilns; WBGT 28.0°C–28.2°C; high radiant heat	Core temperature, sweat rate, and urine-specific gravity	71% of women worked above safe heat limits, 87% of those without toilet access reported genitourinary issues due to intentional dehydration to avoid urination.
(Venugopal et al., 2023)	India	Cross-Sectional	Salt-pan workers; n = 352	Outdoor moderate-to-heavy work, with mean WBGT values of approximately 27.8–30.5°C	Tympanic temperature, heart rate, sweat rate, body-mass loss, urine-specific gravity, creatinine, uric acid, and eGFR	Fifteen percent experienced tympanic-temperature increases exceeding 1°C, and 28% had elevated post-shift urine-specific gravity. Reduced kidney function was more prevalent among men.
(Rowlinson & Jia, 2014)	Hong Kong	Field study	Construction workers; n = 216	Outdoor construction work under hot and humid summer	Tympanic temperature, heart rate, blood pressure, and blood glucose	The study developed locally applicable WBGT thresholds for heavy and ordinary construction work using

Study	Country	Design	Worker population and sample	Occupational heat exposure	Physiological outcomes	Principal findings
				conditions		a predicted heat-strain model.
(Venugopal et al., 2020)	India	Cross-Sectional	Outdoor workers (subset); n = 1094	Outdoor salt pan, agriculture, brick, construction; avg. WBGT 30.1°C	Core temperature, sweat rate, urine-specific gravity, serum creatinine, eGFR, and renal ultrasonography	Risk of physiological strain was 3.6 times higher in groups with high workload and heat; salt pan workers had 2.9 times higher risk of decreased eGFR.
(Gallo-Ruiz et al., 2019)	Nicaragua	Cohort	Brickmaking workers; n = 224	Outdoor work and intense oven heat	Serum creatinine, eGFR, uric acid, and proteinuria	CKD prevalence was 12.1%, with all identified cases occurring among men. Oven-related work was an important occupational predictor.
(Venugopal et al., 2026)	India	Cross-sectional	Agricultural, construction, brick-kiln, and other outdoor workers; n = 596	Outdoor heat exposure, with summer WBGT of approximately 31.7°C	Core temperature, heart rate, sweat rate, body-mass loss, urine-specific gravity, proteinuria, haematuria, creatinine, and eGFR	Heat exposure was associated with increased core temperature, heart rate, and dehydration. Heat-exposed workers had a 2.1-fold higher risk of eGFR below 90 mL/min/1.73 m².

Outdoor occupational heat exposure resulted from direct solar radiation, high ambient temperature, humidity, radiant heat from kilns, and metabolic heat generated during physical work. Workers were commonly exposed during agriculture, construction, sugarcane harvesting, brickmaking, salt production, fishing, plantation work, and other field-based activities. WBGT was the most frequently reported environmental heat indicator, with average values generally ranging from approximately 19°C to 32°C. Some workers were exposed to ambient temperatures above 40°C, while daily exposure commonly lasted four to more than eight hours. Heat exposure was frequently accompanied by moderate-to-heavy physical workload, prolonged work periods, and limited access to rest, shade, drinking water, or sanitation. Environmental heat alone did not consistently predict physiological or renal outcomes. Differences in workload, exposure duration, job task, hydration practices, workplace controls, and occupational co-exposures contributed to variation across worker populations.

Physiological Responses to Outdoor Occupational Heat Exposure

The reported physiological responses were classified into thermoregulatory, cardiovascular, hydration, and renal domains. Overall, outdoor occupational heat exposure was associated with increased body temperature, elevated heart rate, physiological strain, sweating, dehydration, and indicators of kidney dysfunction. Higher heat exposure and heavier workloads were generally associated with increased body temperature, heart rate, sweating, and physiological strain. Migrant workers more frequently experienced core-temperature increases exceeding 1°C, while 15% of salt-pan workers showed similar tympanic-temperature increases. Heart rate increased consistently, whereas blood-pressure findings were limited and inconsistent. Dehydration was commonly indicated by elevated urine-specific gravity, inadequate fluid intake, and body-mass loss. Migrant workers had a 3.2-fold higher dehydration risk than local workers, and 28% of salt-pan workers had elevated post-shift urine-specific gravity. Among female outdoor workers, inadequate toilet access encouraged intentional fluid restriction and increased genitourinary risks. Renal findings included elevated serum creatinine, reduced eGFR, acute kidney injury, proteinuria, haematuria, CKD, and tubular-injury biomarkers. Acute kidney injury occurred in 12.3% of agricultural workers after one shift. Kidney-injury biomarkers also increased among sugarcane workers during harvest. A

structured rest, shade, hydration, and hygiene intervention reduced kidney injury and inflammatory indicators. Reduced kidney function was more common among male salt-pan workers, while CKD prevalence among brickmaking workers was 12.1%. However, measured heat exposure did not consistently correspond with renal outcomes.

Sex-Related Evidence

Most studies included both female and male outdoor workers, although several samples were male-predominant. One study involved only female outdoor workers. The availability and strength of sex-specific evidence differed substantially across studies. he direct within-study comparisons are summarized in Table 2.

Table 2.
Direct within-study evidence concerning sex-related physiological responses

Study	Outcome domain	Direct sex-related finding	Important contextual considerations
Kwaro et al (2025)	Thermoregulatory and cardiovascular strain	Women had a higher mean physiological strain index and peak heart rate than men despite similar activity levels.	Small sample and a single subsistence-farming setting.
De Silva et al. (2022)	Renal function and CKDu	Sex was not independently associated with CKDu susceptibility after multivariable adjustment.	Occupational group, age, agrochemical exposure, and sex distribution varied across occupations.
Moyce et al. (2017)	Physiological strain and acute kidney injury	High physiological strain was associated with AKI among men, whereas piece-rate work and employment duration were associated with AKI among women.	Occupational roles, employment arrangements, and work histories differed by sex.
Laws et al. (2016)	Renal-injury biomarkers	Women had higher baseline NGAL and IL-18, but harvest-related changes did not differ by sex.	The female subgroup was small, and occupational tasks differed substantially.
Venugopal et al. (2023)	Kidney function	Women had higher baseline NGAL and IL-18, but harvest-related changes did not differ by sex.	Analyses adjusted for age and exposure duration, but task and behavioural differences may have remained.

Some studies indicated greater cardiovascular and composite physiological strain among women. Female Kenyan farmers had a higher physiological strain index and peak heart rate than men despite similar measured physical activity. Female outdoor workers also showed greater sensitivity to heat-related symptoms in one large occupational sample. In contrast, a greater renal burden was reported among men in several occupations. Reduced kidney function was more prevalent among male salt-pan workers, while all CKD cases among Nicaraguan brickmaking workers occurred in men. However, these patterns were influenced by differences in occupational role, physical workload, exposure duration, and employment conditions. Female workers also experienced context-specific vulnerability related to sanitation. Limited toilet access encouraged intentional fluid restriction, increasing dehydration and genitourinary risks. This finding represents an occupational and organizational pathway rather than direct evidence of inherently greater physiological susceptibility. Overall, the evidence did not demonstrate that either female or male outdoor workers were consistently more susceptible across all physiological domains.

DISCUSSION

The most consistent findings were increased body temperature, heart rate, sweating, physiological strain, and dehydration, whereas renal outcomes ranged from tubular-injury biomarkers to acute kidney injury and reduced estimated glomerular filtration rate. These findings agree with previous reviews showing that occupational heat exposure increases core and skin temperatures, heart rate, and urine-specific gravity among outdoor workers (Flouris et al., 2018; Ioannou, Foster, et al., 2022; Ioannou, Mantzios, et al., 2022). The first research question is therefore answered by showing

that occupational heat exposure produces multisystem physiological strain rather than a single isolated response.

Thermoregulatory and cardiovascular responses showed the clearest patterns. Outdoor workers are simultaneously exposed to ambient heat, solar radiation, humidity, and metabolic heat generated during physical work. When total heat gain exceeds the body's heat-dissipation capacity, body temperature, sweating, skin blood flow, and cardiovascular demand increase(Gagnon & Kenny, 2012). The frequent increases in heart rate and physiological strain identified in this review are therefore physiologically plausible. However, the magnitude of these responses depended on workload, exposure duration, clothing, acclimatization, and opportunities for rest and cooling (Ioannou, Foster, et al., 2022; Ioannou, Mantzios, et al., 2022). Hydration disturbances were also common, particularly among agricultural, migrant, and salt-pan workers. Elevated urine-specific gravity, inadequate fluid consumption, and body-mass loss indicated that sweating was not always matched by sufficient fluid replacement. Fluid loss can reduce plasma volume and increase cardiovascular and renal stress, particularly during prolonged physical work(Nerbass et al., 2017). Nevertheless, hydration status was strongly influenced by drinking opportunities, workload, sanitation, and work organization. Moreover, body-mass loss was not consistently associated with acute kidney injury, indicating that a single hydration indicator cannot fully represent the pathways linking heat exposure to renal dysfunction(Moyce et al., 2017).

Renal abnormalities represented an important component of the physiological burden. Acute kidney injury was identified after a single agricultural shift, while changes in serum creatinine, eGFR, NGAL, IL-18, proteinuria, and other indicators were reported among sugarcane, agricultural, salt-pan, and brickmaking workers. Harvest-related increases in tubular-injury biomarkers were particularly evident among workers performing physically intensive field tasks, while electrolyte intake was associated with more favourable biomarker profiles in some groups (Laws et al., 2016). Repeated heat strain, strenuous workload, dehydration, and incomplete recovery may therefore contribute to both acute and cumulative kidney injury, although inflammation, muscle damage, hyperuricemia, and other occupational exposures may also be involved(Chapman et al., 2021; Nerbass et al., 2017).

However, measured environmental heat did not consistently predict renal outcomes. In Sri Lanka, the occupational group with the highest heat exposure had the lowest CKDu susceptibility, whereas occupation, age, and agrochemical exposure were more strongly associated with abnormal kidney function (De Silva et al., 2022). Similarly, short-term dehydration indicators were not uniformly related to acute kidney injury (Moyce et al., 2017). These findings suggest that WBGT and ambient temperature should be interpreted together with metabolic workload, cumulative exposure, hydration practices, occupational co-exposures, and recovery opportunities. Heat is therefore an important contributor but is unlikely to be the sole determinant of kidney dysfunction across all outdoor occupations.

Evidence concerning sex-related differences was limited and varied across physiological domains. Female Kenyan farmers demonstrated higher physiological strain index and peak heart rate than men despite similar measured activity, suggesting greater cardiovascular and composite strain in that specific setting(Kwaro et al., 2025). Conversely, greater renal impairment was reported among men in salt-pan and brickmaking occupations (Gallo-Ruiz et al., 2019; Venugopal et al., 2023). These findings do not demonstrate a universal female or male disadvantage because men were often concentrated in heavier and hotter tasks, and several studies had strongly sex-imbalanced samples. Broader evidence similarly indicates that observed sex differences depend on body morphology, metabolic heat production, fitness, acclimatization, dehydration, and occupational exposure rather

than sex alone (Gagnon & Kenny, 2012; Wesseling et al., 2020; Wickham, McCarthy, et al., 2021; Wickham, Wallace, et al., 2021).

Workplace organization further complicated sex-related interpretation. Female outdoor workers sometimes restricted fluid intake because toilets were unavailable or inadequate, increasing dehydration and genitourinary risks (Venugopal et al., 2016). This represents an organizationally mediated vulnerability rather than evidence of inherently lower heat tolerance. Likewise, physiological strain was associated with acute kidney injury among men, whereas piece-rate payment and longer agricultural employment were more relevant among women in one field study(Moyce et al., 2017). Sex-related outcomes should therefore be interpreted in relation to occupational segregation, workload, employment arrangements, migration, sanitation, and access to protective resources.

A major strength of this review is its outdoor-worker focus and its integrated assessment of thermoregulatory, cardiovascular, hydration, and renal outcomes. It also distinguishes direct within-study sex comparisons from limited and contextual evidence, preventing the inclusion of women and men in the same sample from being misinterpreted as evidence of a sex difference. Nevertheless, confidence in the findings is limited by the predominance of cross-sectional and short-duration field studies, heterogeneous exposure and outcome measurements, limited control of confounding, and underrepresentation of women in several occupations. The concentration of evidence in tropical and subtropical settings also restricts generalizability. In addition, searching only Scopus and English-language articles may have omitted relevant studies, while methodological heterogeneity prevented quantitative pooling(Flouris et al., 2018; Ioannou, Foster, et al., 2022).

The findings support multicomponent heat-management programmes combining environmental monitoring, workload-adjusted rest schedules, shade, drinking water, electrolyte replacement, sanitation, worker education, and physiological or renal surveillance. Among Nicaraguan sugarcane workers, progressively strengthened rest, shade, hydration, and hygiene measures were associated with substantial reductions in kidney injury, acute kidney injury, inflammation, and leukocyturia (Hansson et al., 2025). However, intervention effectiveness depends on implementation quality, management commitment, and worker participation rather than water provision alone (Glaser et al., 2022). Future studies should use prospective or repeated-measures designs, recruit balanced female and male samples, compare workers performing equivalent tasks, and report objective physiological outcomes separately by sex. Such evidence is needed to distinguish acute reversible strain from cumulative organ injury and to develop equitable protection strategies for outdoor workers.

CONCLUSION

Outdoor occupational heat exposure causes multisystem physiological strain, including thermoregulatory, cardiovascular, hydration, and renal disturbances, while evidence of consistent sex-related susceptibility remains inconclusive. Practice and policy should prioritize integrated heat controls, hydration, sanitation, rest, and health surveillance, while future research should use prospective designs, standardized measures, and balanced sex-disaggregated samples.

DECLARATIONS

Acknowledgment: The authors acknowledge the valuable contributions of previous studies that formed the basis of this systematic review.

Conflicts of interest: The authors declare no conflicts of interest.
Ethical approval: Not required, as this study is based on previously published literature

Financial support and sponsorship: This research received no funding.

Data Availability Statement: All data supporting the findings of this review are available in the published studies cited in this article.

Author Contributions: All authors contributed to the conceptualization, literature review, data analysis, and manuscript preparation. All authors reviewed and approved the final manuscript.

Declaration of the Use of Artificial Intelligence in Scientific Writing: AI was used for language editing and grammatical refinement. The authors reviewed and verified the manuscript and take full responsibility for its content.

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