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Combined impact of heat and dust on diabetes hospitalization in Kuwait

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ABSTRACT

Introduction In Kuwait, a severe diabetes and obesity epidemic coexists with intense dust storms and harsh summer heat. While, theoretically, this interplay between dust, heat, and diabetes presents a serious public health problem, the empirical understanding of the actual risks remains limited. We hypothesized that increased exposure to heat and dust, independently and jointly, exacerbates the risk of hospitalization for diabetes patients.

Research design and methods We placed custom-designed particle samplers in Kuwait to collect daily dust samples for 2 years from 2017 to 2019. Samples were analyzed for elemental concentrations to identify and quantify dust pollution days. Temperature data were collected from meteorological stations. We then collected hospitalization data for unplanned diabetic admissions in all public hospitals in Kuwait. We used a case-crossover study design and conditional quasi-Poisson models to compare hospitalization days to control days within the same subject. Finally, we fitted generalized additive models to explore the smoothed interaction between temperature and dust days on diabetes hospitalization.

Results There were 11 155 unplanned diabetes hospitalizations over the study period. We found that each year, there was an excess of 282 diabetic admissions attributed to hot days (95% CI: −14 to 473). Additionally, for every 10 μg/m^3 increase in dust levels, there were about 114 excess diabetic admissions annually (95% CI: 11 to 219). Compared with mild non-dusty days (33°C (0 μg/m^3)), hot–dusty days jointly increased the relative risk of diabetic admissions from 1.11 at 42°C (85 μg/m^3) to 1.36 at 42°C (150 μg/m^3).

Conclusions Both heat and dust seem to contribute to the increased diabetes morbidity, with combined hot–dusty conditions exacerbating these risks even further.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ There is a high prevalence of diabetes and obesity in Kuwait, accompanied by severe environmental conditions such as extreme heat and dust storms, which are theorized to exacerbate health complications in diabetics.

WHAT THIS STUDY ADDS

⇒ This study provides empirical evidence that both extreme heat and dust storms independently and jointly increase hospitalization rates for diabetic patients in Kuwait.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This study points to healthcare systems who should start to integrate environmental risk factors into clinical practices and policies, ensuring preparedness for the compounded health impacts of extreme climate conditions on vulnerable populations, such as diabetics.

INTRODUCTION

In the harsh desert environment of Kuwait, there is (1) an alarming diabetes and obesity epidemic, (2) dramatic dust storms and dust haze that frequently blanket the country year-round, and (3) extremely hot summers with record-breaking temperatures. The simultaneous interplay between two major environmental phenomena and a public health epidemic in Kuwait provides a unique window to study the effects of the environment on diabetes.

The Kuwait Diabetes Epidemiology Program reported a diabetes prevalence among adults at 19.1%, significantly higher than the global average of 9%, with a staggering 64.8% prevalence in individuals over 60 years.[1 2] Additionally, 74% of the adult population are either overweight or obese.[3 4] Diabetes medications alone accounted for 22.8% of the nation's drug expenditures in 2018, roughly US$218 million.[5]

Within the same context, the country faces the harshest extreme weather events. Every year, more than 270 tons of dust are deposited in every kilometer square in Kuwait.[6] In the southern part of the country, air pollution from fine particulate matter ($PM_{2.5}$; particulate matter with aerodynamic diameter less than 2.5 microns) exceeded the daily WHO limits in almost 90% of the days.[7] Meanwhile, summer temperatures frequently surpass 50°C, with a record high of 54°C in 2016.[8 9] These unprecedented hot temperatures are expected to escalate with the progression of climate change.[10]

Diabetic patients are thought to be vulnerable to air pollution and extreme heat.[11–15] The increased heat sensitivity in diabetics can be attributed to impaired sweat production, reduced blood flow to the skin, and diabetic peripheral neuropathy, which together impair heat dissipation and temperature regulation.[16] Furthermore, fine dust particles can induce endothelial damage and oxidative stress, exacerbating vascular complications and systemic inflammation, thus worsening diabetic outcomes.[17 18] While, theoretically, this interplay between dust, heat, and diabetes presents a serious public health crisis, the empirical understanding of the actual risks remains limited. We leveraged the presence of amplified exposures and the high proportion of diabetics to collect data on temperature, dust, and hospital admissions throughout Kuwait. The aim was to investigate the short-term impact of hot and dusty days on the acute hospitalization admission rates of individuals with diabetes. We hypothesized that increased exposure to heat and dust, independently and jointly, exacerbates the risk of hospitalization for diabetes patients.

METHODS

Dust data

For the period from October 2017 to October 2019, we placed particle samplers at two locations in Kuwait to collect daily samples of $PM_{2.5}$ (in µg/m^3). These samplers were custom designed at the Harvard T.H. Chan School of Public Health (known as 'Harvard Impactor').[19] They were made capable of collecting large quantities of particles during dust storms using a polyurethane foam impaction substrate to efficiently collect particles above specific size thresholds, proving to be very accurate and precise in the challenging desert environment (figure 1).[7 20 21] Daily collected samples were then shipped to Boston, Massachusetts, for speciated analysis of elemental concentrations. Trace elements were detected using Energy Dispersive X-Ray Fluorescence. Quality assurance measures and protocols were developed by the Harvard T.H. Chan School of Public Health, ensuring reliable data collection and analysis as outlined in Alahmad *et al*.[7]

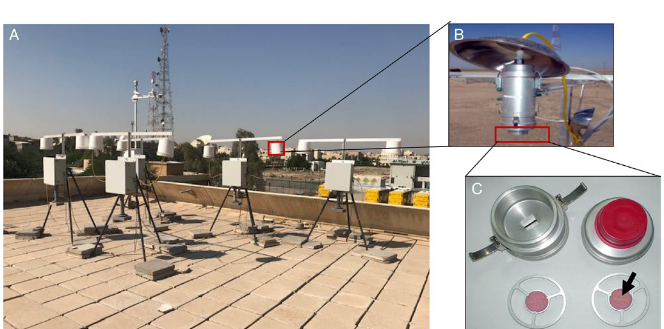

Figure 1 Dust collection process showing (A) a sampling location in Kuwait, (B) custom-designed Harvard Impactors, and (C) the acceleration jet and polyurethane foam that can enable accurate dust collection (the arrow shows a large amount of accumulated dust in the rectangular yellow surface).

Speciation data (elemental concentrations) for each day during the sampling period were fitted in positive matrix factorization models.[22] These models discern 'source factors' based on statistical correlations and variations in the data, effectively separating and identifying distinct pollution sources by their unique compositional profiles. To single out the dust pollution (as opposed to traffic or fossil fuel burning pollution), we relied on the presence of high loadings from fingerprint crustal and geological elements (eg, Mg, Al, Si, Ca, Ti, and Fe).[23 24] Correlation between measured fingerprint elements and the sourced overall dust concentration is shown in online supplemental figure S1. In this analysis, for each day, we calculate the average from the two locations to get the daily observed dust-sourced $PM_{2.5}$ (in µg/m^3).[25] This is referred to as 'dust' onwards.

Temperature data

Daily temperature (in °C) data were obtained from Kuwait International Airport from the Meteorological Department of the Directorate General of Civil Aviation in Kuwait. Airport data is known for its comprehensive record of hourly weather data extending back to the 1960s. Additionally, the Kuwait Environmental Public Authority conducts regular monitoring of meteorological indicators, including 24-hour daily average temperatures and relative humidity, gathered from 15 meteorological stations across urban areas in Kuwait. We selected the Airport data for this analysis due to its completeness and the lack of significant heterogeneity across the small geographic distribution of urban areas.[26]

Hospitalization data

The Ministry of Health keeps records of discharge forms (that subsequently get digitized) for every hospitalization. We obtained all 'non-planned' hospital admissions for diabetes mellitus from 14 public hospitals in Kuwait (7 general hospitals and 7 peripheral/tertiary hospitals). The data was available by the admission date and discharge diagnosis classified by the International Classification of Diseases 10 revision. We analyzed all admitted patients for diabetes mellitus causes (E10–E14), which includes type 1, type 2, and unspecified. The data structure did not enable us to detect multiple hospitalizations by the same individual. The admissions data were available from 1 January 2010 to 31 December 2020. We excluded the year 2020 because of the COVID-19 disruption to healthcare access.

Study design

We used a case-crossover design where each subject serves as their own control. This extension of the conventional case–control studies allows for a comparison within the same subject and, therefore, eliminates confounding at the individual level (eg, by age, sex, body mass index, smoking, etc).[27] We compared temperature and dust concentrations during the day of hospitalization (case) to other days of the same day of the week (effectively 1 week apart) within the same month and the same year when the same individual was not hospitalized (self-control).

Statistical analysis

We fitted a conditional quasi-Poisson model with eliminated strata of a three-way interaction between day of the week, month, and year. The conditional Poisson models are efficient alternatives to conditional logistic models.[28] Model specification is presented in online supplemental methods.

To estimate the effects of heat, we restricted the analysis to the hottest three summer months (June, July, and August) from 2010 to 2019. Temperature was fitted using distributed lag non-linear models (DLNM) that simultaneously model the temperature and lag dimensions.[29] We used a short lag of 7 days with two natural spline knots placed equally on the log scale. Temperature was modeled with two natural spline knots placed at the 50th and 90th percentiles. The relative risk of diabetes hospitalization was calculated by comparing hot summer days to the lowest summer temperature day (33°C, rounded to the whole number). We summed up the contribution of each summer day using Gasparrini and Leone extension to calculate attributable risk.[30]

When estimating the effects of dusty days, we used all months from 2017 to 2019. Using penalized splines,[31] we did not find evidence of non-linearity in the dust and hospitalization dose–response relationship. Dust was then fitted linearly in models adjusted for temperature, relative humidity, and anthropogenic-source pollution (regional $PM_{2.5}$). We used a 7-day moving average to account for the lag effect. The relative risk of diabetes hospitalization was reported for every 10 µg/m^3 increase in dust level. The attributable risk was calculated by multiplying the risk fraction by the total diabetes admissions per year.

We then used a generalized additive model to fit an interaction penalized spline[31] for two continuous variables: 7-day moving average of temperature and dust. From the resulting smoothed three-dimensional relationship (dust–temperature–diabetes), we obtained predictions at three dust scenarios: no dust (0 µg/m^3), high dust (85 µg/m^3), and very high dust day (150 µg/m^3), and used them to calculate the relative risk of diabetic hospitalization from summer hot days.

All analyses were done using R software (V.4.2.1) and the DLNM, MGCV, and Plotly packages.

Table 1 Descriptive analysis of the study population and the environmental exposures

	Summers only* (2010–2019)	Year long† (2017–2019)
Diabetes mellitus admissions, n (average per day)		
Total	8960 (9.7)	11 155 (10.0)
Male	4618 (5.0)	5814 (5.3)
Female	4342 (4.7)	5341 (4.9)
Elderly (65+ years)	1804 (2.1)	1687 (1.7)
Diabetes type, n		
Type 1	1730 (1.9)	1950 (1.8)
Type 2	288 (0.3)	350 (0.3)
Unspecified	6942 (7.5)	8855 (8.1)
Environmental factors, mean±SD (min, max)		
Temperature (°C)	39.1±1.9 (33.2, 44.0)	27.9±9.7 (7.0, 43.6)
Relative humidity (%)	16.5±9.5 (6.3, 65.9)	37.8±20.5 (9.1, 92.4)
Dust (µg/m^3)	23.8±29.5 (1.7, 189.1)	17.3±26.7 (0, 290.4)

*Summers include the hottest 3 months of the year (June, July, and August); used for the heat analysis.
†Dust sampling took place from 2017 to 2019; used for the dust and heat–dust interaction analyses.

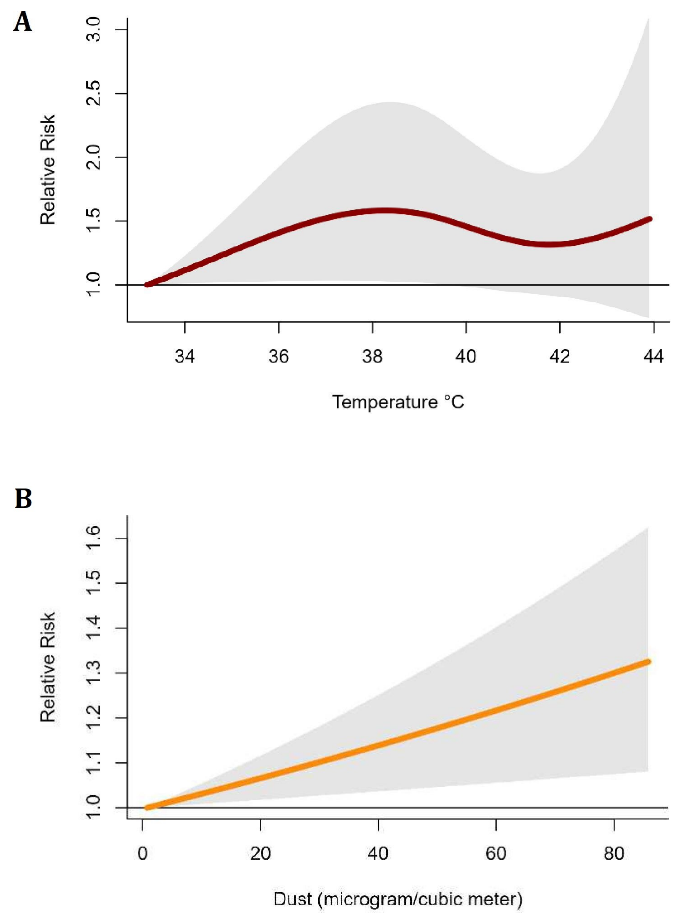

Figure 2 Dose–response relationship showing the relative risk of diabetes hospital admissions for (A) summer heat and (B) dust in Kuwait.

RESULTS

The total number of unplanned hospital admissions for diabetes mellitus was 11 155 all year long from 2017 to 2019 (table 1 and online supplemental table S1). For the summer months (June to August) from 2010 to 2019,

Table 2 Overall and stratified relative risk of diabetes hospitalization for heat and dust exposure in Kuwait

	Total	Male	Female	Elderly (65+ years)
	Relative risk (95% CI)			
Heat				
33.0°C	Reference	Reference	Reference	Reference
34.0°C	1.11 (1.01 to 1.23)	1.13 (0.99 to 1.29)	1.09 (0.95 to 1.26)	1.10 (0.90 to 1.35)
35.0°C	1.26 (1.02 to 1.57)	1.30 (0.97 to 1.73)	1.21 (0.89 to 1.65)	1.23 (0.79 to 1.92)
36.0°C	1.41 (1.03 to 1.92)	1.45 (0.95 to 2.22)	1.33 (0.85 to 2.09)	1.37 (0.72 to 2.61)
37.0°C	1.52 (1.03 to 2.24)	1.57 (0.93 to 2.65)	1.43 (0.82 to 2.50)	1.49 (0.67 to 3.31)
38.0°C	1.58 (1.03 to 2.42)	1.62 (0.91 to 2.88)	1.50 (0.81 to 2.78)	1.58 (0.65 to 3.84)
39.0°C	1.56 (1.02 to 2.39)	1.56 (0.88 to 2.78)	1.52 (0.82 to 2.82)	1.63 (0.67 to 3.97)
40.0°C	1.46 (0.99 to 2.15)	1.41 (0.83 to 2.38)	1.49 (0.85 to 2.62)	1.63 (0.72 to 3.69)
41.0°C	1.35 (0.94 to 1.92)	1.25 (0.77 to 2.03)	1.44 (0.86 to 2.41)	1.64 (0.79 to 3.44)
42.0°C	1.32 (0.91 to 1.91)	1.20 (0.72 to 1.99)	1.43 (0.83 to 2.44)	1.76 (0.82 to 3.77)
43.0°C	1.39 (0.84 to 2.31)	1.27 (0.63 to 2.55)	1.47 (0.71 to 3.03)	2.03 (0.74 to 5.60)
44.0°C	1.52 (0.74 to 3.13)	1.40 (0.52 to 3.78)	1.53 (0.55 to 4.26)	2.39 (0.58 to 9.86)
Dust				
For every 10 μg/m^3 increase	1.03 (1.00 to 1.06)	1.01 (0.98 to 1.05)	1.05 (1.01 to 1.09)	1.03 (0.97 to 1.10)

there were a total of 8960 hospital admissions. Distribution of admissions across the years is presented in online supplemental figure S2.

During the summer months, the average temperature was at 39.1°C (27.9°C for the year-long period), with a considerably narrower SD in summer, indicating less variation and a hot prolonged period (table 1). The climate was also characterized by dry heat with average relative humidity during summers as low as 16.5% (± 9.5%). Dust concentration averaged at 23.8 μg/m^3 during summers. The year-long average of dust concentrations in Kuwait was 17.3 μg/m^3 (± 26.7 μg/m^3), although with a broader range from no dust days (0 μg/m^3) to severe dust storms (290.4 μg/m^3).

Figure 2 represents the dose–response relationships for heat and dust (independently) and the relative risk of diabetes hospitalization in Kuwait during the study period. For dust particles, the relationship shows a linear increase in risk as dust concentration rises. For every 10 micrograms per cubic meter increase in dust, the risk of hospitalization for diabetes increased by 3% (relative risk=1.03, 95% CI: 1.00 to 1.06) translating into about 114 excess diabetic admissions annually (95% CI: 11 to 219) (table 2).

For the heat in summer months, the curve demonstrates a non-linear relationship where the relative risk increases substantially as temperatures rise from the summer minimum of 33°C, reaching a peak at around 38°C, then fluctuates and shows another smaller peak around 43°C (figure 2). Compared with the 33°C as a reference, the relative risk of hospitalization at 34°C was 1.11 (95% CI: 1.01 to 1.23); at 35°C was 1.26 (95% CI: 1.02 to 1.57); and this risk continued to increase, peaking at 38°C with a relative risk of 1.58 (95% CI: 1.03 to 2.42) (table 2). We found that each year, there were an excess of about 282 diabetic admissions attributed to hot days that were above 33°C (95% CI: −14 to 473). We observed almost a similar pattern among subgroups such as males versus females (p value=0.14) (table 2).

In three-dimensional smoothing, the temperature slope at extreme dust is less pronounced compared with the dust slope at extreme temperatures (online supplemental figure S3). In interaction analysis (table 3), compared with mild temperature non-dusty days (33°C (0 μg/m^3)), hot–dusty days jointly increased the relative risk of diabetic admissions from 1.11 (95% CI: 0.85 to 1.45) at 42°C (85 μg/m^3) to 1.36 (0.70 to 2.62) at 42°C (150 μg/m^3). These findings of compounded risk of combined exposures warrant cautious interpretation, given the lack of precision in interaction models.

DISCUSSION

Kuwait's extreme climate, being one of the hottest and dustiest environments globally, offers a unique natural laboratory to study the impacts of hot and dusty days on the incidence and management of an existing epidemic of diabetic patients. Our findings show that, in Kuwait, both heat and dust contribute to increased diabetes hospitalizations, with combined hot–dusty conditions seem to be exacerbating these risks even further.

There are several hypotheses that suggest diabetics may react to heat more intensely than healthy individuals. This increased heat sensitivity could be due to impaired sweat production and reduced blood flow to the skin, which are common in diabetes and can impair heat dissipation.[16] Additionally, diabetic peripheral neuropathy and vascular damage may affect the body's ability to

Table 3 Interaction of hot–dusty days and the relative risk of diabetes hospitalization in Kuwait

Hot days	No dust day<1 µg/m^3	High dust day 85 µg/m^3	Very high dust day 150 µg/m^3
	Relative risk (95% CI)		
33.0°C	Reference	1.09 (0.87 to 1.36)	1.33 (0.69 to 2.55)
34.0°C	0.99 (0.90 to 1.10)	1.09 (0.87 to 1.37)	1.33 (0.69 to 2.56)
35.0°C	0.99 (0.89 to 1.10)	1.09 (0.87 to 1.38)	1.33 (0.69 to 2.56)
36.0°C	0.98 (0.88 to 1.10)	1.10 (0.87 to 1.38)	1.34 (0.69 to 2.57)
37.0°C	0.98 (0.87 to 1.09)	1.10 (0.87 to 1.39)	1.34 (0.70 to 2.58)
38.0°C	0.97 (0.86 to 1.09)	1.10 (0.86 to 1.40)	1.34 (0.70 to 2.59)
39.0°C	0.97 (0.85 to 1.09)	1.10 (0.86 to 1.42)	1.35 (0.70 to 2.60)
40.0°C	0.96 (0.85 to 1.09)	1.11 (0.86 to 1.43)	1.35 (0.70 to 2.60)
41.0°C	0.95 (0.84 to 1.09)	1.11 (0.85 to 1.44)	1.35 (0.70 to 2.61)
42.0°C	0.95 (0.83 to 1.09)	1.11 (0.85 to 1.45)	1.36 (0.70 to 2.62)

regulate temperature.[16] With heightened exposure, the pathophysiology here suggests pathways leading to three adverse outcomes that could lead to unplanned hospitalization for diabetic patients: worsening foot ulcers, hypoglycemia, and hyperglycemia. First, warm temperatures could promote bacterial growth,[32] which, when coupled with the compromised healing capabilities inherent in diabetic patients, can significantly exacerbate the severity of diabetic foot ulcers.[33] Second, thermal stress is associated with an increase in catabolic hormones such as epinephrine, glucagon, cortisol, and growth hormone, which serve as insulin antagonists.[34] This hormonal surge may lead to a counter-regulatory response that precipitates hypoglycemia. Adding complexity to this scenario, heat also seems to enhance the absorption of subcutaneously injectable insulin, further increasing the risk for hypoglycemia.[35] Finally, heat-induced fluid loss and subsequent dehydration can disrupt metabolic control, heightening the risk of hyperglycemic crises such as diabetic ketoacidosis in type 1 diabetics.[36]

When individuals breathe in dust, the fine particles (those lower than 2.5 µm in diameter) travel down to the pulmonary alveoli, where they can cross into the bloodstream. This translocation can lead to endothelial damage, as the particles directly injure the vascular endothelium. The resultant endothelial dysfunction is a recognized factor in the progression of vascular complications in diabetics.[17] Concurrently, the presence of these dust particles can induce oxidative stress, overwhelming the body with free radicals leading to potential cellular damage, especially in tissues that are already susceptible due to hyperglycemic conditions.[17,18] Additionally, the systemic inflammation triggered by the air pollution particles further exacerbates the chronic inflammatory state inherent to diabetes.[37] This could precipitate acute diabetic complications, such as poor wound healing, an increased risk of infections, and cardiovascular events.

Exploring the interactive effects of air pollution and air temperature on health is increasingly gaining momentum, as these two exposures often occur simultaneously. Several studies have investigated this interaction in various geographic locations, focusing on hospital admissions[38–40] and mortality, both within specific regions[41] and globally across multiple countries and cities.[42,43] These previous studies predominantly focused on cardiovascular and respiratory causes. To our knowledge, though, this is the first epidemiological assessment of such combined effects of harsh environmental conditions on diabetes. While earlier research has linked an increased risk of diabetes to carbonaceous particles emitted from man-made pollution sources,[11,12] the impact of intensified natural dust storms on diabetes remains poorly understood.[44] Dust events in the Middle East are increasing in frequency and severity due to a warming climate, causing more droughts.[45,46] To isolate the effects of natural dust from other pollutants, we collected primary dust samples and analyzed their epidemiological impact on a population level. Additionally, prior studies have indicated that elevated temperatures can escalate the risk and complications associated with diabetes.[13] However, the extreme heat observed in Kuwait, as reported in our study, is unlike most studied locations. The evidence we provide here is suggestive that the combined hot–dusty conditions may synergistically increase susceptibility among diabetics and increase healthcare costs and burdens.

This study has a number of limitations. Initially, our air pollution sampling campaign was designed to extend over at least 3 years; however, it was prematurely stopped in 2020 due to the COVID-19 lockdowns. The stoppage of funding also prevented us from restarting the air sampling. Despite this, with only 2 years of speciated dust data, we were still able to detect a statistically significant effect. However, expectedly, the interaction analysis was likely underpowered. Nevertheless, we argue that the effect estimates were strongly suggestive of worsening outcomes from combined hot–dusty conditions. Moreover, our approach aggregated data across types of diabetes, which may obscure differences in environmental susceptibility among patients with type 1, type 2, and unspecified diabetes. Surprisingly, the majority of discharge forms, completed by attending physicians, did not specify the type of diabetes. We were logistically unable to find the discharge forms and recode them. This was a lost opportunity to gain a deeper insight into the pathophysiological impacts of environmental factors on diabetes and its complexities. A limitation of this analysis is also the potential misclassification of exposures to heat and air pollution, as it is expected that subjects would spend most of their day indoors, whereas our measurements were taken from outdoor monitors. This discrepancy likely led to inaccuracies in exposure assessment. Additionally, physical activity, which is known to improve blood glucose control in type 2 diabetes, is likely reduced on days with high dust and heat, potentially exacerbating diabetic conditions. Finally, the geographical specificity to Kuwait, although a strength in understanding unique climate impacts, may limit the generalizability of our findings to regions with different climates and healthcare systems.

CONCLUSION

In today's climate change, more regions find themselves unprepared to handle healthcare strains posed by intensive heatwaves and the potential transboundary desert dust. This study shows the role of extreme climate conditions on diabetic health in a country with one of the highest rates of obesity and diabetes globally. Environmental exposures do not happen in isolation; whether independently or jointly, they could contribute to increased diabetes hospitalizations. The diabetes healthcare professional community cannot afford to ignore emerging environmental risk factors.

Contributors BA, HA, and FA-M conceptualized the idea and commissioned the research analysis. BA and YA did the data cleaning and analysis. BA wrote the first draft of the manuscript. All authors significantly contributed to the planning, conduct, and reporting of this manuscript. BA had full access to the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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Patient consent for publication Not applicable.

Ethics approval This study was approved by the Dasman Diabetes Institute Ethical Review Committee (reference: RA MoH-2024-003).

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REFERENCES

1 Alkandari A, Alarouj M, Elkum N, *et al*. Adult Diabetes and Prediabetes Prevalence in Kuwait: Data from the Cross-Sectional Kuwait Diabetes Epidemiology Program. *J Clin Med* 2020;9:3420.
2 Saeedi P, Petersohn I, Salpea P, *et al*. Global and regional diabetes prevalence estimates for 2019 and projections for 2030 and 2045: Results from the International Diabetes Federation Diabetes Atlas, 9th edition. *Diabetes Res Clin Pract* 2019;157:107843.
3 Abarca-Gómez L, Abdeen ZA, Hamid ZA. Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults. *Lancet* 2017;390:2627–42.
4 Our World in Data. Obesity: when did obesity increase? How do rates vary across the world? n.d. Available: https://ourworldindata.org/obesity
5 Alowayesh MS, Aljunid SM, Al-Adsani A, *et al*. Utilization and cost of drugs for diabetes and its comorbidities and complications in Kuwait. *PLoS One* 2022;17:e0268495.
6 Al-Dousari A, Al-Awadhi J. Dust fallout in northern Kuwait, major sources and characteristics. *Kuwait J Sci* 2012;39:171–87.
7 Alahmad B, Al-Hemoud A, Kang C-M, *et al*. A two-year assessment of particulate air pollution and sources in Kuwait. *Environ Pollut* 2021;282:117016.
8 Alahmad B, Al-Hemoud A, Al-Bouwarthan M, *et al*. Extreme heat and work injuries in Kuwait's hot summers. *Occup Environ Med* 2023;80:347–52.
9 Merlone A, Al-Dashti H, Faisal N, *et al*. Temperature extreme records: World Meteorological Organization metrological and meteorological evaluation of the 54.0°C observations in Mitribah, Kuwait and Turbat, Pakistan in 2016/2017. *Intl J Climatol* 2019;39:5154–69.
10 Intergovernmental Panel Climate Change. *Climate change 2021: the physical science basis - The Working Group I contribution to the sixth assessment report*. IPCC WG I, 2021.
11 Wang B, Xu D, Jing Z, *et al*. Effect of long-term exposure to air pollution on type 2 diabetes mellitus risk: a systemic review and meta-analysis of cohort studies. *Eur J Endocrinol* 2014;171:R173–82.
12 Eze IC, Hemkens LG, Bucher HC, *et al*. Association between ambient air pollution and diabetes mellitus in Europe and North America: systematic review and meta-analysis. *Environ Health Perspect* 2015;123:381–9.
13 Song X, Jiang L, Zhang D, *et al*. Impact of short-term exposure to extreme temperatures on diabetes mellitus morbidity and mortality? A systematic review and meta-analysis. *Environ Sci Pollut Res Int* 2021;28:58035–49.
14 Zanobetti A, Dominici F, Wang Y, *et al*. A national case-crossover analysis of the short-term effect of PM2.5 on hospitalizations and mortality in subjects with diabetes and neurological disorders. *Environ Health* 2014;13:38.
15 O'Neill MS, Veves A, Sarnat JA, *et al*. Air pollution and inflammation in type 2 diabetes: a mechanism for susceptibility. *Occup Environ Med* 2007;64:373–9.
16 Kenny GP, Sigal RJ, McGinn R. Body temperature regulation in diabetes. *Temperature (Austin)* 2016;3:119–45.
17 Rajagopalan S, Brook RD. Air pollution and type 2 diabetes: mechanistic insights. *Diabetes* 2012;61:3037–45.

18 Kampfrath T, Maiseyeu A, Ying Z, *et al*. Chronic fine particulate matter exposure induces systemic vascular dysfunction via NADPH oxidase and TLR4 pathways. *Circ Res* 2011;108:716–26.
19 Demokritou P, Gupta T, Ferguson S, *et al*. Development and laboratory performance evaluation of a personal cascade impactor. *J Air Waste Manag Assoc* 2002;52:1230–7.
20 Brown KW, Bouhamra W, Lamoureux DP, *et al*. Characterization of particulate matter for three sites in Kuwait. *J Air Waste Manag Assoc* 2008;58:994–1003.
21 Alolayan MA, Brown KW, Evans JS, *et al*. Source apportionment of fine particles in Kuwait City. *Sci Total Environ* 2013;448:14–25.
22 Hopke PK. Recent developments in receptor modeling. *J Chemom* 2003;17:255–65.
23 Kavouras IG, Koutrakis P, Cereceda-Balic F, *et al*. Source apportionment of PM_{10} and $_{PM2.5}$ in five Chilean cities using factor analysis. *J Air Waste Manag Assoc* 2001;51:451–64.
24 Vaccaro S, Sobiecka E, Contini S, *et al*. The application of positive matrix factorization in the analysis, characterisation and detection of contaminated soils. *Chemosphere* 2007;69:1055–63.
25 Colonna KJ, Alahmad B, Choma EF, *et al*. Acute exposure to total and source-specific ambient fine particulate matter and risk of respiratory disease hospitalization in Kuwait. *Environ Res* 2023;237:117070.
26 Alahmad B, Tomasso LP, Al-Hemoud A, *et al*. Spatial Distribution of Land Surface Temperatures in Kuwait: Urban Heat and Cool Islands. *Int J Environ Res Public Health* 2020;17:2993.
27 Jaakkola JJK. Case-crossover design in air pollution epidemiology. *Eur Respir J Suppl* 2003;40:81s–5s.
28 Armstrong BG, Gasparrini A, Tobias A. Conditional Poisson models: a flexible alternative to conditional logistic case cross-over analysis. *BMC Med Res Methodol* 2014;14:122.
29 Gasparrini A, Armstrong B, Kenward MG. Distributed lag non-linear models. *Stat Med* 2010;29:2224–34.
30 Gasparrini A, Leone M. Attributable risk from distributed lag models. *BMC Med Res Methodol* 2014;14:55.
31 Wood SN, Pya N, Säfken B. Smoothing parameter and model selection for general smooth models. *J Am Stat Assoc* 2016;111:1548–63.
32 Tsuji A, Kaneko Y, Takahashi K, *et al*. The effects of temperature and pH on the growth of eight enteric and nine glucose non-fermenting species of gram-negative rods. *Microbiol Immunol* 1982;26:15–24.
33 Yavuz M, Ersen A, Hartos J, *et al*. Temperature as a Causative Factor in Diabetic Foot Ulcers: A Call to Revisit Ulceration Pathomechanics. *J Am Podiatr Med Assoc* 2019;109:345–50.
34 Brenner I, Shek PN, Zamecnik J, *et al*. Stress hormones and the immunological responses to heat and exercise. *Int J Sports Med* 1998;19:130–43.
35 Koivisto VA, Fortney S, Hendler R, *et al*. A rise in ambient temperature augments insulin absorption in diabetic patients. *Metab Clin Exp* 1981;30:402–5.
36 Miyamura K, Nawa N, Nishimura H, *et al*. Association between heat exposure and hospitalization for diabetic ketoacidosis, hyperosmolar hyperglycemic state, and hypoglycemia in Japan. *Environ Int* 2022;167:107410.
37 Zanobetti A, Schwartz J. Cardiovascular damage by airborne particles: are diabetics more susceptible? *Epidemiology* 2002;13:588–92.
38 Huang F, Luo Y, Guo Y, *et al*. Particulate Matter and Hospital Admissions for Stroke in Beijing, China: Modification Effects by Ambient Temperature. *J Am Heart Assoc* 2016;5:e003437.
39 Hsu W-H, Hwang S-A, Kinney PL, *et al*. Seasonal and temperature modifications of the association between fine particulate air pollution and cardiovascular hospitalization in New York state. *Sci Total Environ* 2017;578:626–32.
40 Yitshak-Sade M, Bobb JF, Schwartz JD, *et al*. The association between short and long-term exposure to $PM_{2.5}$ and temperature and hospital admissions in New England and the synergistic effect of the short-term exposures. *Sci Total Environ* 2018;639:868–75.
41 Zhou L, Wang Y, Wang Q, *et al*. The interactive effects of extreme temperatures and $PM_{2.5}$ pollution on mortalities in Jiangsu Province, China. *Sci Rep* 2023;13:9479.
42 Rai M, Stafoggia M, de'Donato F, *et al*. Heat-related cardiorespiratory mortality: Effect modification by air pollution across 482 cities from 24 countries. *Environ Int* 2023;174:107825.
43 Stafoggia M, Michelozzi P, Schneider A, *et al*. Joint effect of heat and air pollution on mortality in 620 cities of 36 countries. *Environ Int* 2023;181:108258.
44 Sadeghimoghaddam A, Khankeh H, Norozi M, *et al*. Investigating the effects of dust storms on morbidity and mortality due to cardiovascular and respiratory diseases: A systematic review. *J Educ Health Promot* 2021;10:191.
45 Li J, Garshick E, Al-Hemoud A, *et al*. Impacts of meteorology and vegetation on surface dust concentrations in Middle Eastern countries. *Sci Total Environ* 2020;712:136597.
46 Alahmad B, Khraishah H, Althalji K, *et al*. Connections Between Air Pollution, Climate Change, and Cardiovascular Health. *Can J Cardiol* 2023;39:1182–90.