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Non-carcinogenic health risks assessment of bioaerosols. ☆,☆☆

Azhar Siddique*, Kashif Rasool*

Qatar Environment and Energy Research Institue (QEERI), Hamad Bin Khalifa University, Doha, Qatar

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ABSTRACT

Bioaerosols, pose potential health risks, yet quantitative assessments of non-carcinogenic risks from bioaerosol inhalation are limited. This study introduces a novel approach for assessing non-carcinogenic health risks using bioaerosol exposure data. The method employs the Average Daily Dose and Hazard Quotient (HQ) metrics, adapted from US Environmental Protection Agency guidelines, with the Reference Dose (RfD) based on thresholds from the National Institute of Occupational Safety and Health and the American Conference of Governmental Industrial Hygienists. This study utilizes a time-weighted approach, considering age-specific inhalation rates and body weights, to enhance the precision of lifetime exposure assessments. This methodology was applied to data collected over one year across multiple locations in Qatar, assessing seasonal and site-specific variations in risk. Results indicate generally low health risks, with HQ values below 1 for most sites and seasons. However, the study identified elevated HQ values at highly active sites during the dry summer, suggesting potential health concerns that need urgent attention. The proposed framework offers a replicable approach for evaluating bioaerosol-related health risks across diverse environments.

- Novel adaptation of HQ-based risk assessment for bioaerosols in Qatar, incorporating a time-weighted approach.
- Evaluation of seasonal and site-specific exposure dynamics.
- Designed for replicability in different environmental conditions.

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* Corresponding authors.
E-mail addresses: azsiddique@hbku.edu.qa (A. Siddique), krasool@hbku.edu.qa (K. Rasool).

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Background

Bioaerosols, composed of airborne biological particles such as bacteria, fungi, viruses, and pollen, are increasingly recognized as a significant environmental health concern, particularly in arid climates with high population densities. Inhalation of bioaerosols is associated with a range of adverse health outcomes, from acute respiratory irritation and allergic reactions to chronic respiratory diseases. Prolonged or high-level exposures may contribute to long-term respiratory impairments, underscoring the need for accurate and site-specific risk assessments for bioaerosols [1,2].

Factors influencing bioaerosol exposure include environmental conditions like temperature and humidity, anthropogenic activities such as agriculture and industrial emissions, and climatic phenomena like dust storms can significantly impact bioaerosol concentrations and health risks [3,4]. Despite these challenges, traditional health risk assessments (HRAs) predominantly focus on chemical pollutants and do not adequately capture the complex behaviors, survival rates, and transmission pathways specific to bioaerosols [5]. Previous studies on bioaerosol inhalation risks have largely used age-limited or pathogen-specific models, focusing on adult or occupational exposure [6,7]. Some incorporated age-specific multiple-path particle dosimetry (MPPD) predictions but were limited to certain environments [8]. The quantitative microbial risk assessment (QMRA) approaches mainly assessed pathogen infection risks in occupational contexts [9].

In contrast, the present study applies an enhanced EPA-based method that calculates lifetime, non-carcinogenic bioaerosol exposure risks by integrating a time-weighted approach. This method accounts for age-specific inhalation rates and body weights across an entire lifetime, thus providing a comprehensive exposure assessment that extends beyond the limitations of adult-only or pathogen-specific models. This study addresses the non-carcinogenic health risks assessment from bioaerosol inhalation, particularly from bacterial and fungal contaminants [2,10]. Building on the United States Environmental Protection Agency (US EPA) risk assessment model traditionally used for chemical pollutants, this approach employs the Average Daily Dose (ADD) and Hazard Quotient (HQ) metrics, adapted to bioaerosol-specific parameters. The updated model incorporates a time-weighted average method, enhancing traditional risk assessments by considering age-specific inhalation rates, body weights, biological decay rates, and site-specific environmental conditions (e.g., extreme temperature and humidity fluctuations) to more accurately reflect lifetime exposure risks. By integrating local environmental data and population-specific variables, this approach provides a quantitative, context-sensitive evaluation of health risks in arid environments. It is designed to be replicable across diverse climates and geographic regions, supporting broader research into bioaerosol-related health risks [5,11].

This study provides an enhanced and adaptable framework incorporating a time-weighted approach for assessing health risks associated with bioaerosol exposure, particularly in vulnerable regions characterized by dust storms, extreme temperatures, and industrial pollution. By integrating age-specific inhalation rates and body weights alongside environmental factors, this methodology advances the broader field of environmental health by offering a tool that can be customized for use in similar environmental contexts [3,4]. It also aligns with reproducibility principles and open science, providing detailed methodological descriptions and validation data to support further research and collaboration within the field [12,13]. Ultimately, this work aims to inform air quality management and guide targeted risk mitigation strategies for bioaerosol exposure across diverse populations.

Method details

Study area and sampling procedure

The bioaerosol sampling campaign was conducted across ten geographically distinct locations in Qatar (Fig. 1), representing various environmental conditions and human activity levels (Table 1). These sites included urban areas such as Al Wakrah and Industrial Area, suburban locations like Al Khore, and rural areas including Dukhan, capturing a range of bioaerosol sources, from residential to industrial emissions [14].

Samples were collected using the Coriolis® μ sampler (Bertin Technologies, France), a high-efficiency air sampler ideal for capturing biological aerosols in liquid media. The sampler was operated at a flow rate of 300 L/min, with sampling conducted at a height of 1.5 m above the ground to simulate human exposure levels. Sampling campaigns were organized across three distinct seasons: winter, dry summer, and humid summer. Approximately 300 samples were collected over the year, ensuring the region's comprehensive seasonal and spatial coverage of bioaerosol diversity [14].

Each site was sampled twice a week, and samples were immediately transported to the laboratory under controlled conditions to preserve bioaerosol integrity. The RNAs-free phosphate buffer (PBS) solution was used as the collection medium, with the sampling duration set at 10 min per site to ensure adequate bioaerosol concentrations for analysis. In the laboratory, Tryptic Soy Agar (TSA) and Malt Extract Agar (MEA) were used to culture bacteria and fungi, respectively. The plates were incubated for three days at 37 °C for bacterial cultures and five days at 25 °C for fungal cultures. Colonies were counted using the positive-hole correction method [15], and concentrations were calculated using colony-forming units per cubic meter (CFU/m^3).

Health risk assessment of bioaerosols

For the first time in Qatar, non-carcinogenic health risks associated with inhalation exposure to bioaerosols among adult males and females were assessed. Unlike previous studies that relied solely on static exposure data, this approach incorporates time-weighted average inhalation rates (TWA-IR) and time-weighted body weights (TW-BW) for a more comprehensive evaluation of lifetime exposure risks. This is the first application of a lifetime exposure assessment for bioaerosols in Qatar and the GCC region, enabling a

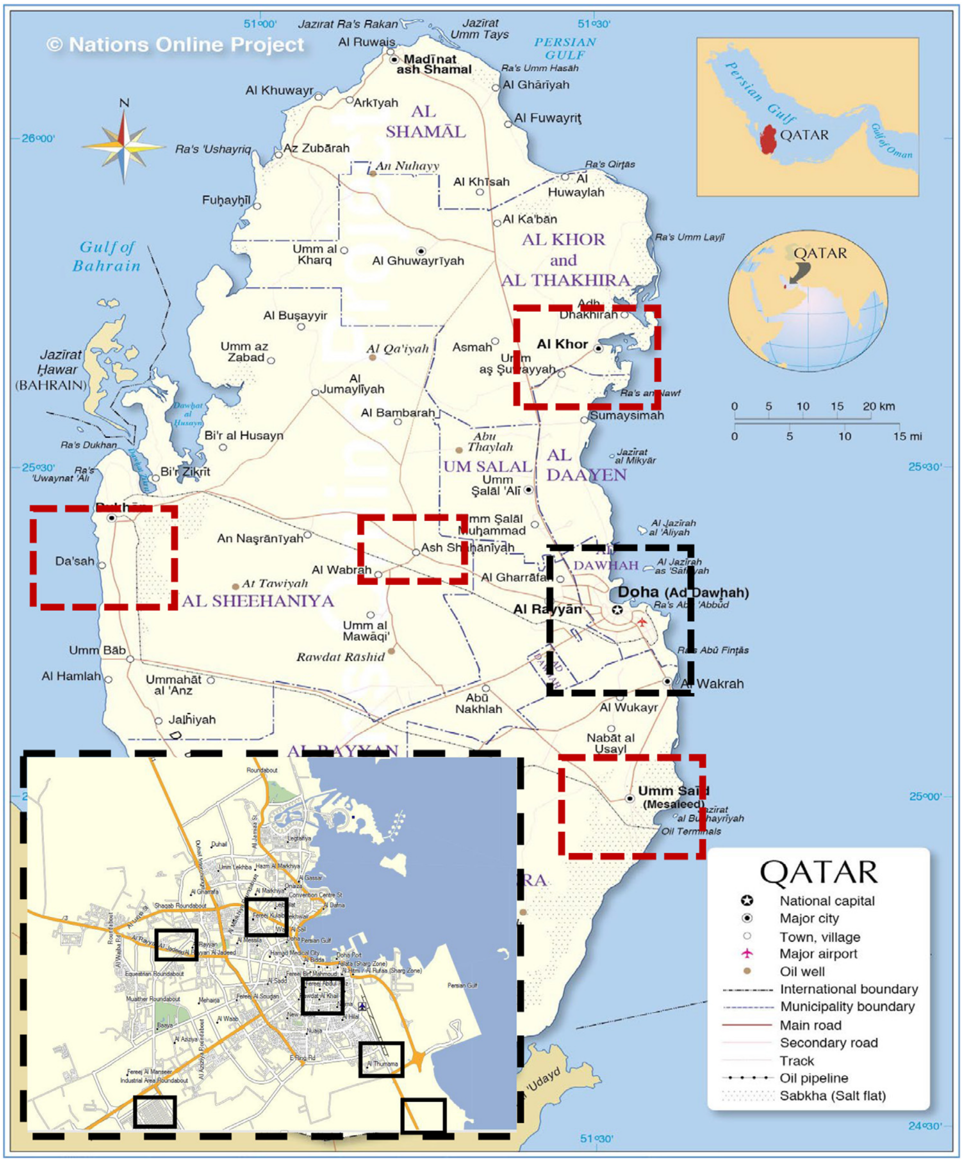

Fig. 1. Map of sampling locations. The inset box represents the sites from the Urban Greater Doha Area (modified after https://www.nationsonline.org/oneworld/qatar.htm).

more nuanced understanding of exposure risks across different age groups. The HRs to calculate the Hazard Quotient (HQ) for non-cancer risks were estimated considering seasonal variations across the sampling sites using the US EPA models [10,16] . The average concentrations for each sampling site and season and the ADD and HQ for bacteria and fungi across male and female populations were estimated. This approach facilitated the detection of variations in exposure risk based on seasons and specific locations, hence assisting in formulating accurate risk management plans. The ADD for inhalation exposure was calculated using the following Eq.1:

$$ADD\left[\frac{CFU}{Kg.day}\right] = \frac{C \times TWA - IR \times ED \times EF}{TWA - BW \times AT} \tag{1}$$

where:

- C represents the average bioaerosols (CFU/m^3) concentration, calculated for each sampling site and season.
- TWA-IR (Time-Weighted Average Inhalation Rate) and TWA-VR (Time-Weighted Average Ventilation Rate) account for variations across different life stages, incorporating age-based activity levels [17,18]. These were calculated using the following time-weighted averaging formula (Table 2):

$$TWA - IR = \frac{\sum \left(\mathrm{IR}_{age\ group}\ x\ duration_{age\ group}\right)}{Total\ Exposure\ Duration} \tag{2}$$

Table 1
Sampling site characteristics.

Site Name	Characteristics
Al-Wakrah	Located near Al-Wakrah General Hospital and close to the coast, downwind of the Greater Doha Area. Busy traffic, proximity to a shopping mall, light commercial activities, represents coastal and downwind urban influences.
Industrial Area	Situated in an area with small to medium processing industries, auto body workshops, and construction material warehouses. High daytime traffic, surrounded by low-cost residential complexes, represents industrial urban activity.
Al-Thumama	Downwind of urban Greater Doha Area, located within the area surrounding a major football stadium. Flanked by two major highways, proximity to a wastewater treatment plant approximately 1500 m to the west, open space.
Al-Muntaza	Represents a densely populated and commercial area in Greater Doha. Surrounded by restaurants and various commercial activities, old and busy area indicating high human activity.
Madinat Khalifa	Located at a busy intersection connecting major roads of Greater Doha. High traffic, residential and commercial surroundings including shopping malls and a health center, urban core area.
RDC (HBKU)	Located in Education City, western part of Greater Doha. Surrounded by educational institutes and a hospital, open and newly developed area for educational purposes with staff housing.
Ash-Shahaniya	North-west of Greater Doha, upwind of urban areas. Suburban, low-density population, nearby camel racing area and a wildlife protected area, occasional high dust levels.
Dukhan	Located on the western seashore, site of early oil and gas exploration. Low population density, large complex of oil and gas processing facilities, employee residential areas, coastal influence.
Al Khore	North of Greater Doha, adjacent to urban expansion. Near Al-Khore Hospital, low-density population with emerging urbanization, proximity to a large gas processing plant, employee housing.
Mesaieed	Southern Qatar near the Saudi border, coastal area. Near beach activity areas, adjacent to oil and gas plant activities, close to the newest port of Doha with significant shipping traffic.

Table 2
Parameters Used in ADD and HQ Calculations for Static and Time-Weighted methods [18,20].

Parameter	Static method (old)	Time-Weighted Average (updated) method
Age- Group	Lifetime- Adult IR and Average Qatari population weight	The age groups were divided into four categories [18} (a)**CHILDREN-** Birth-11 years, (b) **ADOLESCENTS**-12–20 years, (c)**ADULTS**- 21–60 years,and (d) **ELDERLY**- 61+
Inhalation Rate (IR)	Fixed values for adults (male: 19.58 m^3/day, female: 15.98 m^3/day)[17]	Time-weighted values based on age groups (TWA-IR male: 13.86 m^3/day, female 13.77m^3/day)
Body Weight (BW)	Qatari adult average values [20] (male: 85.9 kg, female: 73.9 kg)	Time-weighted values using age-specific data [18,20] (TWA-BW male: 71.5 kg, female 62 kg)
Exposure Duration (ED)	Lifetime (78 years for males, 76 years for females)	Lifetime is divided into four age groups to account for variations in exposure
Averaging Time (AT)	Lifetime (ED × 365 days/year)= male 28,470 days, female 27,740 days	Lifetime (ED × 365 days/year)= male 28,470 days, female 27,740 days
Reference Dose (RfD)[21]	Based on static IR and BW values (male=228 CFU/Kg.day and female=217 CFU/Kg.day)	Calculated using time-weighted IR and BW values for each age group (male = 194 CFU/Kg.day, female = 222 CFU/Kg.day)

This weighted approach enables a more refined estimate of respiratory intake, accommodating physiological changes over time (Table 3).

- EF is the Exposure Frequency.
- ED is the Exposure Duration.
- TWA-BW (Time-Weighted Average Body Weight) integrates changes in body weight across various life stages, providing a more accurate measure for long-term risk assessment. This was calculated as (Table 3):

$$TWA - BW = \frac{\sum \left(\mathrm{BW}_{age\ group}\ x\ duration_{age\ group}\right)}{Total\ Exposure\ Duration} \tag{3}$$

- AT is the Averaging Time, represents the total exposure duration in days.

The HQ was calculated to determine the non-carcinogenic risk of inhalation exposure to each bioaerosol type using Eq.2:

$$HQ = \frac{ADD}{RfD} \tag{4}$$

The Reference Dose (RfD) was calculated using a bioaerosol exposure threshold of 1000 CFU/m^3, based on guidelines from the National Institute for Occupational Safety and Health and the American Conference of Governmental Industrial Hygienists[19]. The RfD values were calculated using the time-weighted approach to reflect population-specific exposure scenarios better (Table 2):

- For each age group, **IR** and **BW** values were applied to calculate exposure (CFU/day).

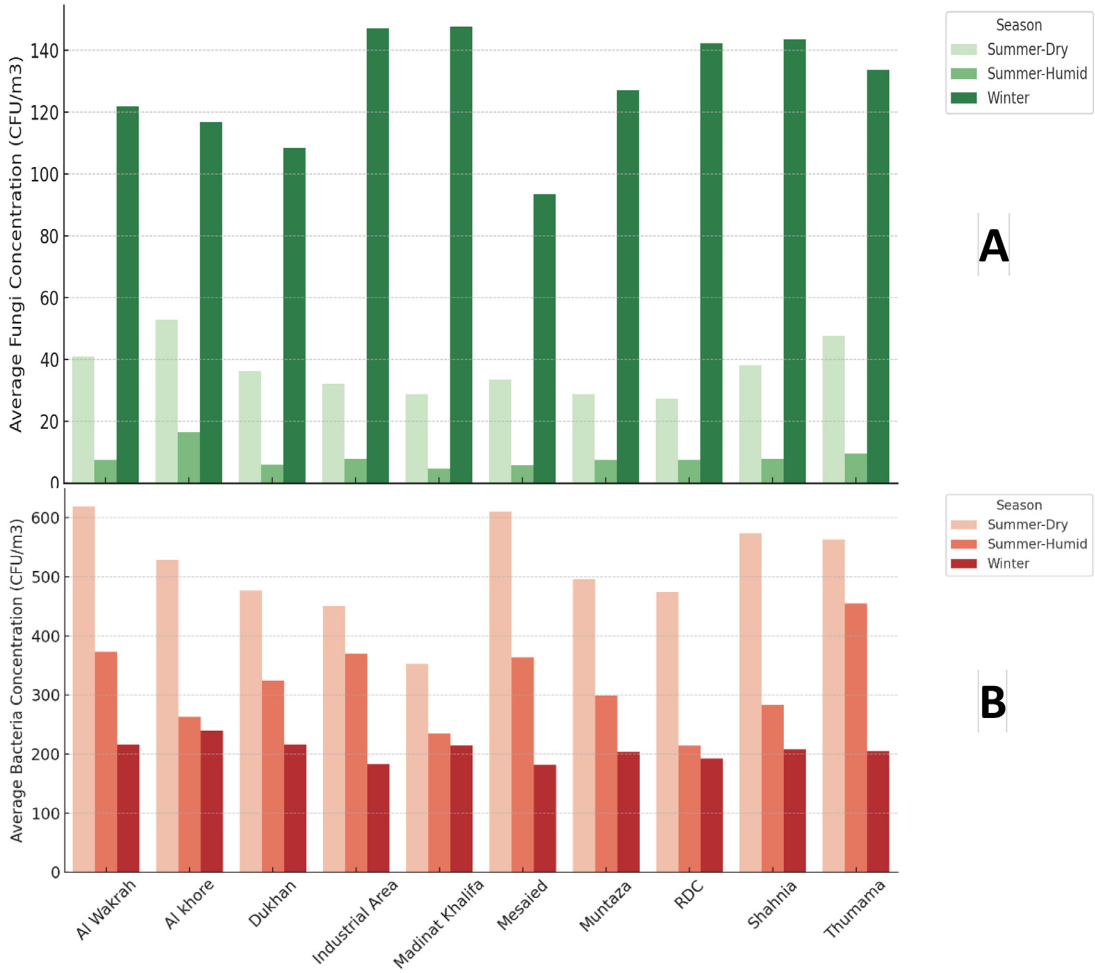

Fig. 2. Average concentration (CFU/m3) of (A) Fungi (B) Bacteria in all seasons and at different locations of the study area.

Table 3
Time Weighted Average group IR and BW used in this study.

Age Group	No of Years	Male Average IR (m^3/day)	Female Average IR (m^3/day)	Male Average BW (kg)	Female Average BW (kg)
0–11 years	12	6.775	6.575	16.25	16.25
12–20 years	9	14.65	13.75	55	55
21–60 years	40	15.75	15.275	85.9	73.9
61+ years	18	13.2	12.95	80	70

- The resulting RfD values were then used to determine HQ for both male and female populations, taking into account variations in IR and BW across different stages of life.

$$RfD_{male/female} = \frac{TW\ Exposure_{male/female}}{TWA - BW_{male/female}} \tag{5}$$

Where;

$$TW\ Exposure_{male/female} = Exposure\ Guideline\left(\frac{CFU}{m^3}\right) x\ TWA - IR_{male/female} \tag{6}$$

This reference dose threshold assesses the potential for adverse health effects over a lifetime. An ADD value below the reference dose suggests a low likelihood of adverse health effects, whereas values exceeding the *RfD* indicate potential adverse human health impacts [21]. Utilizing the USEPA model, an HQ ≤ 1 suggests no expected adverse health effects, while an HQ > 1 signals a probable risk of adverse health outcomes..

Method validation

This study presents a novel methodology for evaluating the non-carcinogenic health risks of bioaerosol inhalation exposure through the HQ metric. This work represents the first effort to establish a quantitative framework for lifetime exposure to bioaerosols health risk in Qatar. Therefore, this method relied heavily on internal validation, methodological consistency, and comparison with established health risk assessment frameworks, particularly those from the US EPA.

The method was applied to our study [14], which revealed the bioaerosol spatial and temporal variability and associated health risks of bacteria and fungi (Fig. 2). We used the conventional or static method and a time-weighted average method to assess and evaluate the lifetime health risk as HQ. The analysis of both methodologies revealed low health risks associated with bacterial and fungal bioaerosol exposure (Table 4). In addition, a comparison was conducted between the original static method (using adult average body weight and IR) and the updated time-weighted (TW) approach to validate the new methodology further. The results revealed significant differences, particularly for females, where the TW method showed higher HQ values, suggesting that the time-weighted approach captures gender-sensitive differences more effectively than the static method. Specifically, for bacterial exposure, the TW method produced significantly higher HQ values for females ($p < 0.001$), with a large effect size (Cohen's $d = 1.87$), indicating a meaningful, practical impact. For fungal exposure, the TW method also showed significantly higher HQ values for females ($p = 0.0059$) with a moderate effect size (Cohen's $d = 0.54$). These findings underscore the importance of using a time-weighted approach to capture subtle yet meaningful variations in exposure risk that static methods may overlook.

HQ values were predominantly below 1 for all evaluated sites and seasons for both genders. The results are consistent with the earlier studies that highlighted the potential health risks of bioaerosols [22]. However, distinct seasonal and site-specific variations were observed. These outcomes emphasize the importance of assessing bioaerosol exposure risks in specific settings.

Table 4
Health risk assessment of Bioaerosols (Bacteria and Fungi) at different sites and seasons in Qatar.

Site	Season	HQ (Static method)				HQ (TWA method)			
		HQ (Bacteria Male)	HQ (Bacteria Female)	HQ (Fungi Male)	HQ (Fungi Female)	HQ (Bacteria Male)	HQ (Bacteria Female)	HQ (Fungi Male)	HQ (Fungi Female)
Al Wakrah	Summer-Dry	6.19E-01	6.17E-01	4.09E-02	4.07E-02	6.19E-01	6.19E-01	4.09E-02	4.09E-02
	Summer-Humid	3.73E-01	3.71E-01	7.53E-03	7.51E-03	3.72E-01	3.73E-01	7.53E-03	7.54E-03
	Winter	2.16E-01	2.15E-01	1.22E-01	1.21E-01	2.16E-01	2.16E-01	1.22E-01	1.22E-01
Al khore	Summer-Dry	5.28E-01	5.26E-01	5.30E-02	5.28E-02	5.28E-01	5.28E-01	5.30E-02	5.30E-02
	Summer-Humid	2.63E-01	2.62E-01	1.64E-02	1.64E-02	2.63E-01	2.63E-01	1.64E-02	1.65E-02
	Winter	2.40E-01	2.39E-01	1.17E-01	1.16E-01	2.40E-01	2.40E-01	1.17E-01	1.17E-01
Dukhan	Summer-Dry	4.77E-01	4.75E-01	3.62E-02	3.61E-02	4.76E-01	4.77E-01	3.62E-02	3.62E-02
	Summer-Humid	3.25E-01	3.24E-01	6.00E-03	5.98E-03	3.25E-01	3.25E-01	6.00E-03	6.01E-03
	Winter	2.15E-01	2.15E-01	1.08E-01	1.08E-01	2.15E-01	2.15E-01	1.08E-01	1.08E-01
Industrial Area	Summer-Dry	4.50E-01	4.49E-01	3.21E-02	3.20E-02	4.50E-01	4.51E-01	3.21E-02	3.21E-02
	Summer-Humid	3.70E-01	3.69E-01	7.83E-03	7.80E-03	3.70E-01	3.70E-01	7.82E-03	7.83E-03
	Winter	1.83E-01	1.82E-01	1.47E-01	1.47E-01	1.82E-01	1.83E-01	1.47E-01	1.47E-01
Madinat Khalifa	Summer-Dry	3.53E-01	3.52E-01	2.88E-02	2.87E-02	3.53E-01	3.53E-01	2.88E-02	2.88E-02
	Summer-Humid	2.34E-01	2.33E-01	4.78E-03	4.77E-03	2.34E-01	2.34E-01	4.78E-03	4.79E-03
	Winter	2.15E-01	2.14E-01	1.48E-01	1.47E-01	2.14E-01	2.15E-01	1.48E-01	1.48E-01
Mesaied	Summer-Dry	6.10E-01	6.08E-01	3.34E-02	3.33E-02	6.10E-01	6.11E-01	3.34E-02	3.35E-02
	Summer-Humid	3.63E-01	3.62E-01	5.82E-03	5.80E-03	3.63E-01	3.64E-01	5.82E-03	5.82E-03
	Winter	1.82E-01	1.82E-01	9.35E-02	9.32E-02	1.82E-01	1.82E-01	9.34E-02	9.35E-02
Muntaza	Summer-Dry	4.96E-01	4.95E-01	2.88E-02	2.87E-02	4.96E-01	4.97E-01	2.88E-02	2.88E-02
	Summer-Humid	2.98E-01	2.98E-01	7.61E-03	7.58E-03	2.98E-01	2.99E-01	7.60E-03	7.61E-03
	Winter	2.04E-01	2.04E-01	1.27E-01	1.27E-01	2.04E-01	2.04E-01	1.27E-01	1.27E-01
RDC	Summer-Dry	4.74E-01	4.73E-01	2.73E-02	2.72E-02	4.74E-01	4.75E-01	2.72E-02	2.73E-02
	Summer-Humid	2.14E-01	2.13E-01	7.53E-03	7.51E-03	2.14E-01	2.14E-01	7.53E-03	7.54E-03
	Winter	1.92E-01	1.91E-01	1.42E-01	1.42E-01	1.92E-01	1.92E-01	1.42E-01	1.42E-01
Shahnia	Summer-Dry	5.73E-01	5.72E-01	3.81E-02	3.80E-02	5.73E-01	5.74E-01	3.81E-02	3.82E-02
	Summer-Humid	2.83E-01	2.82E-01	7.86E-03	7.83E-03	2.82E-01	2.83E-01	7.85E-03	7.86E-03
	Winter	2.08E-01	2.07E-01	1.43E-01	1.43E-01	2.08E-01	2.08E-01	1.43E-01	1.44E-01
Thumama	Summer-Dry	5.63E-01	5.61E-01	4.77E-02	4.75E-02	5.63E-01	5.63E-01	4.77E-02	4.77E-02
	Summer-Humid	4.55E-01	4.53E-01	9.53E-03	9.50E-03	4.54E-01	4.55E-01	9.52E-03	9.53E-03
	Winter	2.05E-01	2.04E-01	1.34E-01	1.33E-01	2.04E-01	2.05E-01	1.33E-01	1.34E-01

To validate the conceptual foundation of the method, the framework developed in this study was aligned with the established principles of non-carcinogenic health risk assessment as outlined by the US EPA. The core components of the HQ calculation—such as exposure duration (ED), exposure frequency (EF) and ventilation rate (VR)—were based on EPA guidelines and adjusted to the local context of Qatar to ensure an accurate reflection of exposure risks. The reference dose (RfD) was derived considering known exposure thresholds and physiological factors and was validated in the context of available guidelines [19]. The HQ values calculated in this study were interpreted against the standard benchmark of HQ $\leq$ 1, which indicates no significant health risks, while HQ > 1 suggests potential adverse health outcomes. Although this is the first study to apply this approach to bioaerosols, it draws on well-established methods for other environmental pollutants, ensuring that the interpretation is consistent with existing non-carcinogenic health risk frameworks.

The study outcomes highlight the importance of considering seasonal fluctuations and site-specific conditions in bioaerosol exposure risk assessments [23]. The health RAs also highlight gender-based variability in risk due to physiological differences, suggesting that future research should better explore the mechanisms behind these differences to understand the health implications of bioaerosol exposure across genders

Seasonal variability in HQs (Table 4) highlights higher Hazard Quotient (HQ) values during the dry summer compared to the humid summer and winter, illustrating the significant impact of climatic conditions on bioaerosol concentrations and associated health risks. This seasonal variation in bioaerosol dynamics is further evidenced by the increased fungal HQ values in winter for specific sites. This suggests that seasonal shifts in environmental conditions significantly influence bioaerosol behaviour [24]. From a site-specific perspective, variations in health risks across different locations underscore the influence of local environmental factors and stressing the need for location-specific health risk assessments and mitigation strategies.

These findings have significant public health implications, particularly for vulnerable populations with pre-existing respiratory conditions or compromised immune systems. Although the overall risk from bioaerosol exposure in the studied areas is generally low, this method can also be applied to indoor air quality health risk assessments using national or regional threshold values—such as 1500 CFU/m^3 in China, 1000 CFU/m^3 in Hong Kong and Singapore, and 500 CFU/m^3 in Malaysia and the UAE [25]. The results underscore the need for precise monitoring and targeted intervention strategies to reduce exposure, especially in areas and seasons identified as higher-risk [26].

Limitations

The presented method for assessing non-carcinogenic health risks of bioaerosol inhalation has several limitations. The lack of epidemiological data limits the direct validation of HQ values with specific health outcomes. The method focuses on culturable bioaerosols, excluding non-culturable organisms, which may underestimate total health risks. Assumptions regarding uniform exposure across the adult population do not account for vulnerable groups such as children and the elderly. In the updated methodology, the time-weighted average (TWA) approach was used to improve the representation of different age groups, but the absence of detailed epidemiological correlation remains a limitation. Additionally, the assessment is based on outdoor concentrations, potentially differing from indoor exposure scenarios. The use of a uniform concentration threshold (1000 CFU/m^3) for bioaerosols may oversimplify risks by not considering the variability in pathogenicity among different species, and cumulative bioaerosol levels do not reflect the diverse health impacts of specific bioaerosol compositions. The findings of higher HQ values for females using the TWA method also highlight the need for more comprehensive gender-specific epidemiological data to understand differential exposure impacts better. Future work should include broader demographic assessments, species-specific analyses, and considerations of indoor environments to improve accuracy and applicability.

Ethics statements

N/A.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Azhar Siddique: Conceptualization, Methodology, Investigation, Validation, Writing – original draft, Writing – review & editing. **Kashif Rasool:** Supervision, Funding acquisition, Project administration, Resources, Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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