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Bioaerosol dispersion and environmental risk simulation: Method and a case study for a biopharmaceutical plant of Gansu province, China

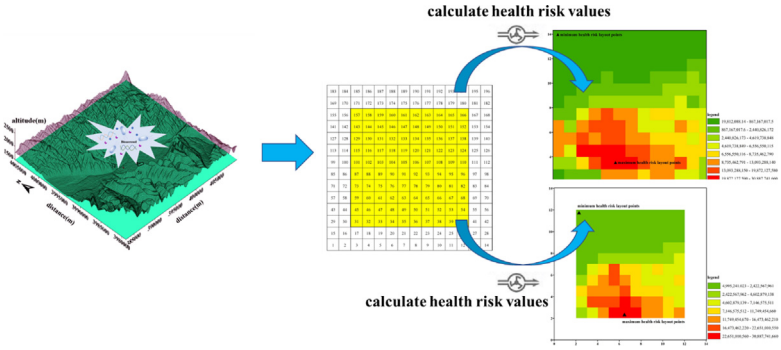
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HIGHLIGHTS

- An integrated risk assessment of bioaerosol leakage was established for the layout of vaccine enterprises.
- Grid computing method was established based on the CALPUFF model and potential environmental risks.
- Population distribution and bioaerosol concentrations had effects on the relative environmental risks of the grid.
- The boundary effect has been considered in the layout and site selection of bioaerosol enterprises.

GRAPHICAL ABSTRACT



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ABSTRACT

Pathogenic bacteria pose a great threat to global public health from environmental and public health perspectives, especially regarding the impact of the COVID-19 pandemic worldwide. As a result, the increased risk of pathogenic bioaerosol exposure imposes a considerable health burden and raises specific concerns about the layout and location of vaccine manufacturers. This study proposed a grid computing method based on the CALPUFF modelling system and population-based environmental risks to reduce bioaerosol-related potential risks. We previously used the CALPUFF model to quantify the diffusion level, the spatial distribution of emissions, and potential environmental risks of bioaerosol leakage in Gansu province's Zhongmu Lanzhou biopharmaceutical plant from July 24, 2019, to August 20, 2019. By combining it with publicly available test data, the credibility was confirmed. Based on our previous research, the CALPUFF model application combined with the environmental population-based environmental risks in two scenarios: the layout and site selection, was explored by using the leakage accident of Zhongmu Lanzhou biopharmaceutical plant of Gansu province as a case study. Our results showed that the site selection method of scenario 2 coupled with the buffer area was more reasonable than scenario 1, and the final layout site selection point of scenario 2 was grid 157 as the optimal layout point. The simulation results demonstrated agreement with the actual survey. Our findings could assist global bioaerosol manufacturers in developing appropriate layout and site selection strategies to reduce bioaerosol-related potential environmental risks.

1. Introduction

The global spread of COVID-19 has increased vaccine demand significantly, putting pressure on vaccine manufacturers (Wouters et al., 2021;

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Roghani and Panahi, 2021). However, the increased risk of vaccine leakage after production can have a negative impact on the environmental ecosystem. In 1979, for example, an accidental anthrax outbreak from an army research institute's laboratory in the former Soviet Union affected 79 people and killed 68 people (Bai et al., 2011). In June 2014, 84 scientists and staff members were exposed to anthrax aerosol contamination at the Centers for Disease Control and Prevention's biological laboratory in Atlanta were exposed to anthrax aerosol contamination, which was the largest laboratory accident involving a potential bioterrorist agent in the United States (D'Amelio et al., 2015). These cases showed that aerosol leakage accidents are extremely difficult to control and cause not only significant health risks but also pose serious challenges to global public health. Additionally, the current studies on environmental risk assessment after vaccine production are not yet complete, especially in areas of exposure assessment and risk characterization (Gregersen, 2008; Chen et al., 2020). Therefore, due to increased vaccine demand and inherent bioaerosol leakage risks, an appropriate layout and site selection of vaccine companies are mandatory to reduce the associated environmental risks arising from vaccine production activities.

Vaccine-related bioaerosol leakage is one of the major air pollutants causing severe disease outbreaks as well as secondary infections due to widespread diffusion in the atmosphere, thus, increasing the global health burden (Singh et al., 2021). Furthermore, several epidemiological and toxicological studies have established evidence of bioaerosols' negative effects on human health (Oh et al., 2020; Zhao et al., 2020). Bioaerosols have a long atmospheric residence time because they contain airborne particles of living cells, pollen, toxins, or microbial derivatives (Walser et al., 2015), they have a long atmospheric residence time (Morakinyo et al., 2016; Ching et al., 2019). As a result, it may increase the risk of human exposure to airborne infections caused by inhalation and ingestion, such as infectious diseases, acute toxic effects, and cancer (Xu and Yao, 2013; Kozdrój et al., 2019; Nag et al., 2021). It has been proposed that various endotoxins and glucans produced by bacteria and molds irritate the airways and significantly increase inflammation (Hoppin et al., 2014). According to Maheswaran et al. (2014), an important fungal cell wall component, 1,3-β-d-glucan (BDG), infected 422 Canadian children and caused atopic/non-atopic asthma and bronchial hyper-responsiveness (Maheswaran et al., 2014). Additionally, aerosols can also spread infectious diseases by carrying viruses such as influenza A (H1N1) and SARS. Various studies have suggested that a potentially significant route of transmission of the COVID-19 infection is aerosol inhalation (Guzman, 2021; Anderson et al., 2020; Asadi et al., 2020). Analogously, the leakage accident at the Zhongmu Lanzhou biopharmaceutical plant of Gansu province in July–August 2019 resulted in the mass infection of tens of thousands of nearby residents due to the diffusion of contaminated aerosols (http://wjw.lanzhou.gov.cn/). Thus, the environmental risks posed by bioaerosol spread and dispersal are undoubtedly a challenge for vaccine manufacturers. Hence, environmental benefits should be considered when deciding on vaccine manufacturers' layout and location.

The CALPUFF model is used to quantitatively study the diffusion aspatial distribution of bioaerosol at different scales. Kritana et al. used the CALPUFF model to simulate the spread of foot-and-mouth disease (FMD) and study the spread of infection from initial epidemic areas to remote places (Kritana et al., 2014). The National Oceanic and Atmospheric Administration's (NOAA) HYSPLIT atmospheric dispersion model used in the Taranto area (Italy) has been used to model the spread of FMD along with epidemiological models to calculate the risk of infection in exposed herds (Coffman et al., 2021). Van Leuken et al. used the Gaussian diffusion model to assess the pathogenic bioaerosol diffusion and quantitative microbial risk. Despite the fact that air quality models have been used to simulate the diffusion, sedimentation, and distribution of microbial derivatives in the atmosphere, little attention has been paid to evaluating the potential impact of bioaerosol diffusion on the population. Therefore, our previous studies used the CALPUFF model to quantitatively simulate the bioaerosol diffusion, concentration, and spatial distribution, as well as evaluate potential health risks in the population of Gansu province's Zhongmu Lanzhou biopharmaceutical plant from July 24, 2019, to August 20, 2019, based on the published data of Lanzhou Veterinary Research Institute (Van Leuken et al., 2016). The results of CALPUFF model and population-based health risk calculation method results were also validated. Based on this, the risk ratio of the two areas agreed with the actual investigation results and validated our study results (Yuan et al., 2020). The results of this research are expected to provide a relevant reference for suitable layout and site selection of vaccine enterprises to reduce bioaerosol-related environmental risks.

In this study, the application of the CALPUFF model combined with the environmental risk method was explored, using the bioaerol leakage accident in the Zhongmu Lanzhou biopharmaceutical plant of Gansu province as a case study. These findings were based on the population calculation in the layout and site selection of microbial aerosol enterprises. This is the first study to incorporate the adverse environmental effects of microbial aerosols and their resultant risks to the population into the layout and site selection of aerosol enterprises in a more quantitative way. It provided new ideas and insights for vaccine manufacturers' existing layout and site selection methods, particularly in the context of COVID-19. Our findings will also be useful for drug manufacturers in China and worldwide looking to reduce their bioaerosol-related environmental risks.

2. Materials and methods

2.1. Study area and subjects

The study domain included the entire Lanzhou urban area, measuring approximately 14 × 14 km^2, and covered the valley and basin area, which was surrounded by mountains, and the east-west Yellow River across the territory. The study conditions were restrained by valley winds and urban heat island circulation, resulting in unfavorable meteorological conditions such as high static wind frequency and frequent temperature inversion (Wu et al., 2021). The study lasted from July 24, 2019, to August 20, 2019. During this time, an expired disinfectant for cleaning was used in Gansu province's Zhongmu Lanzhou biopharmaceutical plant while producing an animal brucella vaccine. Because the disinfectant was unable to sterilize the contaminated waste completely, it leaked into the air as aerosols. It had a significant impact on the Lanzhou Veterinary Research Institute and the surrounding community as a result of factory leakage. According to available data, the infection was confirmed in 10,528 people after 68,571 people were tested up to November 30, 2020 (Pappas, 2022). Lanzhou meteorological station data suggested that east and southeast east winds were the dominant winds, with an average speed of 1.2 m/s, a static wind frequency of 2.4 %, and an average temperature of 23.6 °C observed during this event (Yuan et al., 2020). The two sensitive study areas of interest, Lanzhou Veterinary Research Institute (1#, 233 m, west of the factory) and Lanzhou University (2#, located 3697 m, southwest of the factory), were located in the east and south directions of the biological pharmaceutical factory, as shown in Fig. S1, respectively.

In this study, we discovered that “factory in the city” was a common issue for many early-stage vaccine manufacturers after urbanization began in the cities where these enterprises were located. According to historical satellite images of Lanzhou suggested that there were no residential areas around the pharmaceutical factory during the early stages of construction. Lanzhou's urbanization process resulted in the “factory in the city” appearance (Fig. S2). Due to transportation, policies, and economic benefits, while conducting site selection in the early development phase (Rahman and Kabir, 2019), relatively less consideration was given to inherent environmental benefits. Hence, we simulated and explored the reasonable layout and location of bioaerosol production enterprises and considered the Zhongmu Lanzhou biopharmaceutical plant of Gansu province as our study research area. We also investigated and attempted to reduce certain environmental risks that vaccine manufacturers may pose.

2.2. Data description

The research data included the environmental impact report of the relocation project of the production area, the environmental impact assessment

report, and the enterprise development data of the Zhongmu Lanzhou biological pharmaceutical factory. Furthermore, the observation data of various meteorological parameters (wind speed, wind direction, relative humidity, precipitation, temperature, and pressure) were provided by three ground meteorological stations (Lanzhou, Yuzhong, and Gaolan). The upper air meteorological data was provided by the Weather Research and Forecasting (WRF) mesoscale weather prediction model and consisted of 3D meteorological field data. The geological data for the study area came from the United States Geological Survey (USGS) Earth Resources Observation Systems (EROS) data center (www.usgs.gov/centers/eros), with a terrain data accuracy of 90 m and land use type data accuracy of 30 m (Bo Xin et al., 2015), and the demographic data came from the LandScan 2018 Database model.

2.3. Simulation based on the CALPUFF model

2.3.1. CALPUFF model

California Puff Modelling (CALPUFF), a three-dimensional, non-steady Lagrange diffusion model developed by Exponent, Inc. has a more flexible smoke mass diffusion pattern than the Gaussian model. It used to simulate severe weather with spatio-temporal variations and more complex pollution sources (Li et al., 2021). Under complex terrains and meteorological field conditions, the CALPUFF model outperforms the Gaussian model in terms of accuracy and effectiveness, resulting in a better simulation effect for bioaerosol long-distance transport. Besides, this model is also one of the legal models that are recommended by the Ministry of Ecology and Environment of China and the Environmental Protection Agency of the United States for the pollutant diffusion simulation (Li et al., 2018). The CALPUFF model has been applied in many complex terrains and meteorological field projects in China and has achieved sound simulation effects (Xu et al., 2020; Li et al., 2019; Rzeszutek, 2019). Therefore, the CALPUFF model was chosen for the simulation of bioaerosol diffusion in our study because it has better simulation effects in restoring the meteorological fields in cases of pollution and leakage and has more selectivity in parameter settings than other models, it was selected for the simulation of bioaerosol diffusion in our study.

2.3.2. Model parameter settings

Brucellosis is a zoonotic infectious disease caused by Brucella that spreads through various infection routes such as the respiratory tract, digestive tract, skin, and so on (Tuon et al., 2017). Brucella can survive for a longer periods in different environments due to its high anti-inactivation ability and strong environmental tolerance, it has been reported that the longest survival time of Brucella was 18 months in a favorable environment (Jacob et al., 2020). Additionally, the number and types of variant strains have now increased due to the continuous evolution of storage hosts and the growing phenomenon of host transfer, thus, forming newer species of Brucella (Blanchong et al., 2016). Two Brucella species (S2 and A19 strains) were considered for this study, with a production cycle of 34d.

Several studies have used particulate matter as the transmission carrier to simulate the atmospheric diffusion of microbial bioaerosols. For example, PM10 has been used as the carrier to simulate the release of the *Bacillus anthracis* agent (Madhwal et al., 2020). In our study, PM 0.56 was used as the transmission carrier of Brucella aerosol because PM 0.56 was similar to the size of Brucella aerosol particles, and the wet and dry deposition process was considered in the simulation process (Yuan et al., 2020). However, because information about the source intensity of the accident leakage was not found in the public data, so a source intensity of a constant value of 1 g/(s·m^2) was assumed. Table S1 details the emission source parameters for the CALPUFF model.

2.3.3. Verification method of the simulation results

The CALPUFF model's simulation effect was verified by the environmental risk relative ratio method, and its feasibility was demonstrated by comparing the health risk ratio between the Lanzhou University and Lanzhou Veterinary Research Institute in terms of model simulation and the actual positive rate ratio. The results of health risks in 1# and 2# areas showed that the mean and standard deviation distribution was approximately normal (Yuan et al., 2020). The Monte Carlo simulation method was used to calculate the health risk ratio of the two regions to test the model's accuracy in simulating health risks and the number of cases.

2.4. Set up of different simulation scenarios

While keeping the local economy and traffic conditions in mind, the existing layout and site selection methods of bioaerosol enterprises have formed a relatively complete site selection system. Our study method evaluated the population distribution and diffusion characteristics data in relation to microbial aerosol emission to optimize the layout and location of enterprises and provide supplementation to the existing bioaerosol enterprise locations. The layout site identification process of the vaccine enterprise is shown in Fig. 1. Five major processes determined the layout site identification: (1) The geographical range of the site selection was determined as the simulation range of the model according to the actual project's location; (2) The entire research was divided into grid cells (alternative plots) with a reasonable resolution in terms of the site selection range and enterprise-scale; (3) The CALPUFF model was used to simulate the microbial aerosol diffusion study and obtain the aerosol diffusion contribution results under various source layout scenarios; (4) The environmental risk value (*Pi*) of each grid and the total risk value (*P*) of all grids under different scenarios were computed using the calculation method of environmental risk value defined in this study; (5) The total risk values of all layout scenarios were screened for obtaining the optimal plot with low health risk as the best vaccine enterprise layout site.

In order to compare and analyze the impact of boundary effects on environmental risk values, the site selection optimization method was applied to two scenarios containing buffer grids and using Zhongmu Lanzhou biological pharmaceutical factory as an example (when the layout points are located in the boundary grid, the risk value pertaining to the high concentration area, outside the grid cannot be calculated). The grid resolution in this study was 100 m, with140 grid points in the east-west and north-south directions. The following were the specific settings of the two scenarios:

Scenario 1: The study scope covered the entire area (14 km × 14 km), which was divided into 196 grid cells as alternative plots (Fig. S3). In each scenario, the CALPUFF model simulated the microbial aerosol diffusion in the atmospheric environment using vaccine enterprise emission data and calculated the grid environmental risk value *Pi* and total environmental risk value *P* in each scenario. Additionally, the optimal land was selected according to the total environmental risk value ranks, the location of polluting enterprises, and population distribution.

Scenario 2: Considering the boundary effect of grids, the outermost two layers of 196 grid cells were set as buffer grids and not alternative plots, based on the study area of Scenario 1. Moreover, only inner 100 grid cells (10 km × 10 km) were included in the alternative plot range (yellow area in Fig. 3). The CALPUFF model and population-based environmental risk method were used to simulate the microbial aerosol diffusion in the environment, and the grid environmental risk *Pi* and total environmental risk *P* values were calculated. Similarly, the plot with the lowest total value at risk was deemed the best in terms of polluting enterprise location and population distribution.

2.5. Environmental impact assessment

After considering the population distribution data and Brucella aerosol concentration, the environmental risk-value method, based on Landscan Globa 2018 population data and the CALPUFF model, calculated the potential risk of each grid having a resolution of 100 m × 100 m. Eq. (1) was used to calculate the potential environmental risk values of bioaerosols to the grid area:

$$P_i = R_i \times C_i \tag{1}$$

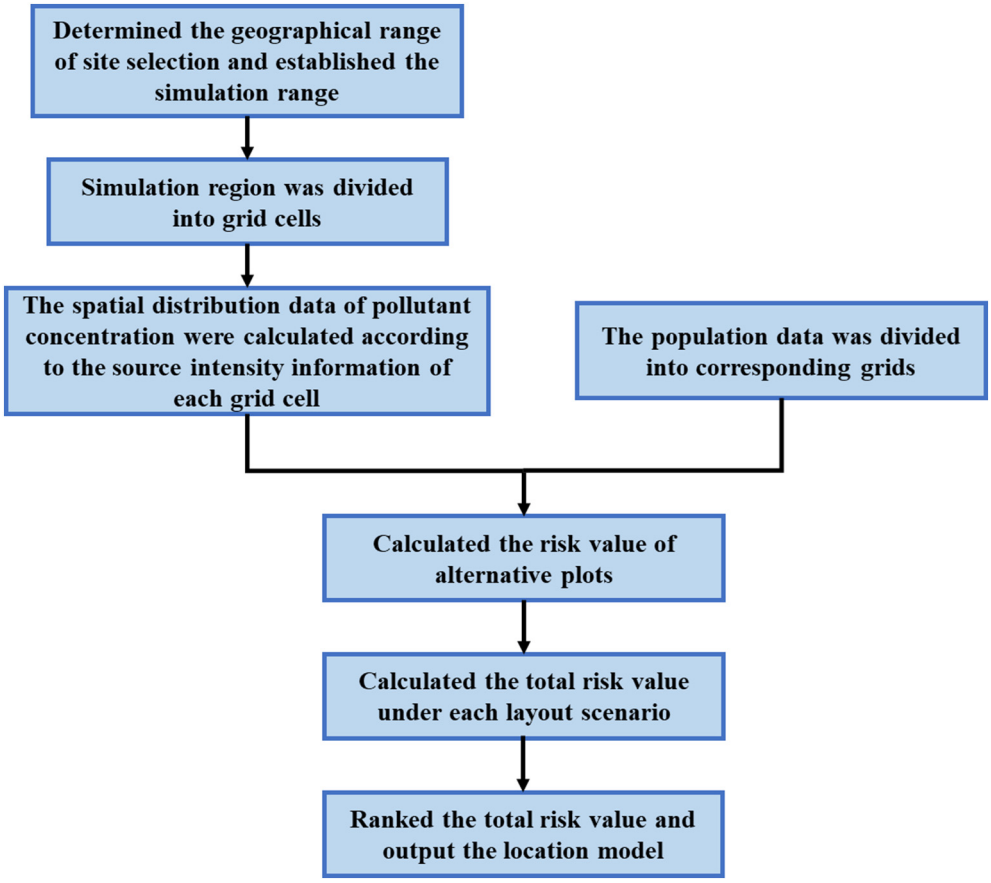


Fig. 1. The flowchart of the layout site identification process of vaccine enterprise.

where R_i is the proportion of the single population grid to the total population in the whole region, C_i is the proportion of the concentration of air pollutant concentration in each grid to the concentration of all grids, and P_i represents an individual grid's environmental risk value.

The P for all grids in both scenarios was calculated using Eq. (2), and i = 1, 2, ……, n.

$$P = \Sigma_{i=1}^{n} P_i \quad (2)$$

3. Results and discussion

3.1. The environmental risk effects of bioaerosol emission

The simulation results of bioaerosol concentration in the study area are shown in Fig. S4. The bioaerosol concentration range was mainly centered in the factory area, and the maximum value appearing near region 1# was 44.70 mg/m^3, and was inconsistent with the dominant wind direction shown in the wind rose diagram of the ground meteorological station (Fig. S5). This occurred due to the differences between the local and regional meteorological parameters caused by uneven terrain, wind direction, and so on (Yuan et al., 2020). The bioaerosol concentration range at Lanzhou Veterinary Research Institute (0.1–20 mg/m^3) was greater than that at Lanzhou University (0.01–0.02 mg/m^3), indicating that the concentration of the Brucella aerosol decreased with an increase in the distance from the factory (Yuan et al., 2020). We also gridded the corresponding population data to investigate the environmental risk effects of bioaerosol (Fig. S6). The results showed that the environmental risk values (253.08–117,886) caused by bioaerosol in 1# area were higher than that in 2# area (198.36–763.29). In addition, the risk ratio for regions 1# area and 2# area was consistent with the publicly reported test results, indicating the reliability and accuracy of our simulation results and the feasibility of the gird computing method for characterizing environmental risks from bacterial-containing aerosols.

3.2. Optimization analysis of vaccine enterprise land layout

The CALPUFF model simulated alternative layout plots and site selection schemes and calculated the total population-based environmental risk values of vaccine manufacturers with regard to surrounding areas under different layout scenarios (Fig. 2). The total health risk values of 196 alternative sites ranged from 1.98×10^7 to 3.09×10^{10} (Table S2), among which the minimum health risk value was in 183 grid in the northwestern region (1.98×10^7). The grid with the highest health risk value (3.09×10^{10}) belonged to the 35 grid in the southern region (scenario 1). The comparison of total environmental risk values of alternative grids in scenario 1 revealed that the grid with the highest total environmental risk value was primarily distributed in the southern study area, which included the densely populated urban area of Lanzhou. As a result of the potential risks involved, this area was unsuitable for vaccine manufacturers due to the involved potential risks. The grids with low total environmental risk values were mainly distributed in the Lanzhou City suburbs, with a small population density in the northern study area. In contrast, the whole environmental risk values induced by factory construction in these grid sites were relatively small. The environmental risk value ranking indicated that the 183 grid in the upper left corner was the optimal site selection grid (Scenario 1).

Without considering the boundary effect, a 2 km buffer area was established based on scenario 1 to surround the enterprise more comprehensively. In scenario 2, only 10 × 10 grids in the inner circle were compared for total environmental risk values, and the risks were 8.96×10^7–3.09×10^{10} (Table S2). The maximum total environmental risk

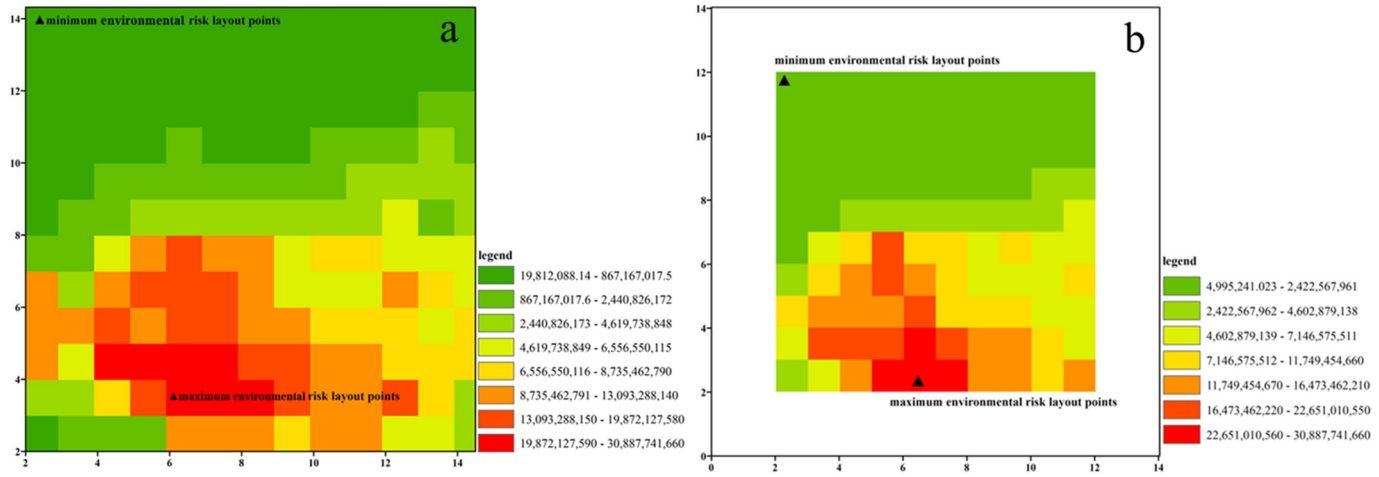


Fig. 2. A comparison of total environmental risk value of each alternative grid in Scenario 1 (a) and Scenario 2 (b).

value appeared in the 35 grid, which was the same as in scenario 1. In the current scenario, the position of the minimum environmental risk value (8.96×10^7) appeared in the 157 grid, thus, this plot served as the optimal site selection. When the results of environmental risk values in scenarios 1 and 2 were compared, the site selection method of scenario 2 with a buffer area was found to be more reasonable. Consequently, the 157 grid was selected as the optimal layout point in the two scenarios as the distribution of people around this grid was less, and the involved environmental risk was lower when compared with the original site of the bioaerosol enterprise.

Based on the CALPUFF model and demographic data simulation results, the environmental risk ratios in the 1# and 2# regions were calculated in which the mean and standard deviation were 36.15 ± 8.48. The calculated risk ratio was 41.49:1 and was within the simulated environmental risk range (36.15 ± 8.48), demonstrating that the simulation results determining the potential impact of bacterial aerosols on the study population were credible.

3.3. Verification of simulation results

In this study, to verify the accuracy and reliability of our simulation results, we compared the maximum environmental risk layout points and the minimum environmental risk layout points under different scenarios with the real plot situation. The results showed that the grid 35 was the maximum environmental risk layout point in scenario 1 and scenario 2. Its corresponding region was in the inner city and densely populated, which was not suitable for the establishment of vaccine enterprise (Fig. 3a). However, in scenario 1 and scenario 2, the minimum environmental risk layout points were grid 183 (Fig. 3b) and grid 157 (Fig. 3c), respectively. Both plots were sparsely populated, making them ideal for the establishing of vaccine plants. In practice, however, factors such as traffic, logistics, groundwater, and infrastructure should be thoroughly considered when locating vaccine companies. Grid 183 was located in the desert area, and the plot corresponding to grid 157 was located near the expressway on the outskirts of the city, and the transportation was more convenient than grid 183. In addition, the grid 157 has fewer environmental risks than the grid 183. Therefore, the grid 157 was the optimal layout point of vaccine enterprise in this study. The above findings demonstrated the study's dependability and rationality.

3.4. Uncertainty analysis

We primarily used population distribution and diffusion characteristics data for bioaerosol emissions in this study to optimize the layout and location of bioaerosol enterprises. However, some uncertainties have yet to be addressed. At first, the main reference information of the bioaerosol concentrations, emissions, time spectrum, and so on in this study was based on the published data from a bioaerosol leakage accident in Gansu province's Zhongmu Lanzhou biopharmaceutical plant and an environmental impact report, which differed from the actual data and may have resulted in inadvertent deficiencies. Secondly, due to the biological attenuation characteristics of bioaerosol, they were affected by temperature, humidity, ultraviolet radiation, and other influencing factors (Jiang et al., 2022). However, these factors were not considered in this study, which may have depicted higher results than the actual values. Additionally, the

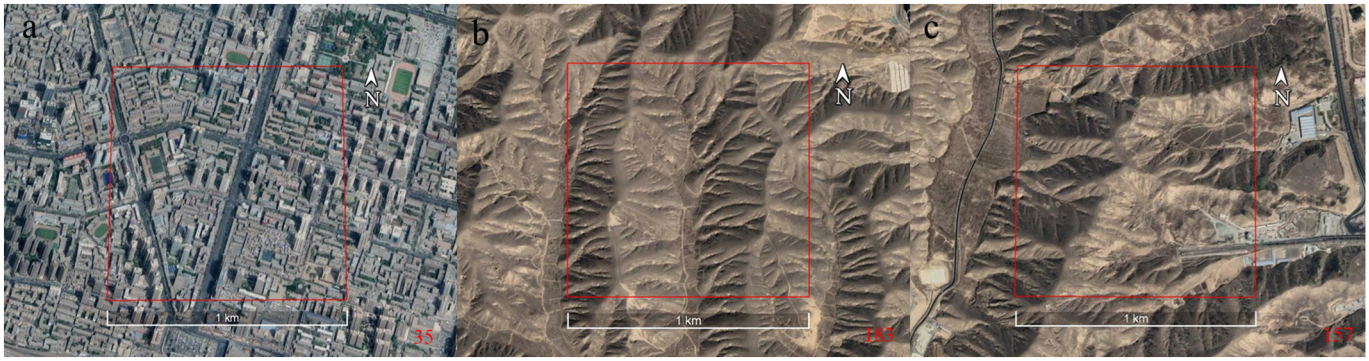


Fig. 3. Image maps of maximum and minimum environmental risk layout points under different scenarios obtained from google earth. a, b, and c represent image maps of grid 35, grid 183, and grid 157, respectively.

gender, age, weight, health, and location of the inhabitants would have affected the infection ability of bioaerosols, which was not taken into account (Guzman, 2021). As the layout point was located in the boundary grid, and the environmental risk value of the high-concentration area outside the grid could not be calculated, the boundary effect could have influenced the calculation results. Despite these uncertainties, this optimized approach can be regarded as a viable option for determining the best layout and location for bioaerosol enterprises.

4. Conclusion

This study used the CALPUFF model to simulate the bioaerosol diffusion process in the atmospheric environment. It investigated the characteristics of simulated microbial aerosol atmospheric diffusion in the Zhongmu Lanzhou biopharmaceutical plant in 2019 based on the brucellosis aerosol leakage. With the Lanzhou LandScan Global 2018 population data, the overall environmental risk of Brucella diffusion was assessed along. Furthermore, the verified simulation results were consistent with the actual survey results, thus, proving the credibility of our results. Based on the previous studies, the application of the CALPUFF model and population-based environmental risk method in the layout and location of Zhongmu Lanzhou biological pharmaceutical factory was explored in two scenarios, one with boundary effect and one without it. After comparing the grid environment risk values under different scenarios, we verified the simulation results with the actual situation and determined that grid 157 was the optimal layout point. This method of research provided a useful reference for the layout and location of bioaerosol enterprises.

More detailed information, however, is required to make the grid computing method more accurately simulate bioaerosol diffusion. Therefore, future research should study the correlation between mass concentration and microbial unit concentration in microbial aerosol and the dose-response effect of environmental diffusion of microbial aerosol to support better the study of the pathogenic risk of microbial aerosol simulation results. In addition, the problem of calculating costs should be taken into account. Therefore, future research should thoroughly consider various factors, such as traffic, population density, costs, etc. Furthermore, these factors can be used to select of preliminary site areas, reducing the CALPUFF model's calculation. These values can then be combined with a population-based environmental risk analysis to determine the best layout and location for vaccine manufacturing units.

CRediT authorship contribution statement

Xin Xu: Conceptualization, Methodology, Software, Writing – review & editing. **Chengxin Wang:** Conceptualization, Writing – review & editing. **Peng Wang:** Writing – review & editing. **Yinghao Chu:** Data curation. **Jing Guo:** Data curation. **Xin Bo:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing, Resources. **Aijun Lin:** Conceptualization, Supervision.

Data availability

Data will be made available on request.

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.

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Appendix A. Supplementary data

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References

Anderson, E.L., Turnham, P., Griffin, J.R., Clarke, C.C., 2020. Consideration of the aerosol transmission for COVID-19 and public health. Risk Anal. 40 (5), 902–907.
Asadi, S., Bouvier, N., Wexler, A.S., Ristenpart, W.D., 2020. The coronavirus pandemic and aerosols: does COVID-19 transmit via expiratory particles? Aerosol Sci. Technol. 54 (6), 635–638.
Bai, J., Xiao, R., Cui, B., Zhang, K., Wang, Q., Liu, X., Gao, H., Huang, L., 2011. Assessment of heavy metal pollution in wetland soils from the young and old reclaimed regions in the Pearl River Estuary, South China. Environ. Pollut. 159 (3), 817–824.
Blanchong, J.A., Robinson, S.J., Samuel, M.D., Foster, J.T., 2016. Application of genetics and genomics to wildlife epidemiology. J. Wildl. Manag. 80 (4), 593–608.
Bo Xin, W.G., Tian, Jun, Yang, Jing-chao, Gao, Xi-zhang, Huang, Yuan-yi, Li, Shi-bei, 2015. Standard systems of surface parameters in AERMOD. China Environ. Sci. 35 (9), 2570–2575 (in Chinese).
Chen, L.-M., Donis, R.O., Suarez, D.L., Wentworth, D.E., Webby, R., Engelhardt, O.G., Swayne, D.E., 2020. Biosafety risk assessment for production of candidate vaccine viruses to protect humans from zoonotic highly pathogenic avian influenza viruses. Influenza Other Respir. Viruses 14 (2), 215–225.
Ching, J., Adachi, K., Zaizen, Y., Igarashi, Y., Kajino, M., 2019. Aerosol mixing state revealed by transmission electron microscopy pertaining to cloud formation and human airway deposition. NPJ Clim. Atmos. Sci. 2 (1), 1–7.
Coffman, M.S., Sanderson, M.W., Dodd, C.C., Arzt, J., Renter, D.G., 2021. Estimation of foot-and-mouth disease windborne transmission risk from USA beef feedlots. Prev. Vet. Med. 195, 105453.
D'Amelio, E., Gentile, B., Lista, F., D'Amelio, R., 2015. Historical evolution of human anthrax from occupational disease to potentially global threat as bioweapon. Environ. Int. 85, 133–146.
Gregersen, J.-P., 2008. A risk-assessment model to rate the occurrence and relevance of adventitious agents in the production of influenza vaccines. Vaccine 26 (26), 3297–3304.
Guzman, M.I., 2021. An overview of the effect of bioaerosol size in coronavirus disease 2019 transmission. Int. J. Health Plann. Manag. 36 (2), 257–266.
Hoppin, J.A., Umbach, D.M., Long, S., Rinsky, J.L., Henneberger, P.K., Salo, P.M., Zeldin, D.C., London, S.J., Alavanja, M.C.R., Blair, A., Beane Freeman, L.E., Sandler, D.P., 2014. Respiratory disease in United States farmers. Occup. Environ. Med. 71 (7), 484–491.
Jacob, J., Finke, A., Mielke, M., 2020. Survival of Brucella abortus S19 and other Brucella spp. in the presence of oxidative stress and within macrophages. Folia. Microbiol. 65 (5), 879–894.
Jiang, G., Ma, J., Wang, C., Wang, Y., Laghari, A.A., 2022. Kinetics and mechanism analysis on self-decay of airborne bacteria:biological and physical decay under different temperature. Sci. Total Environ. 832, 155033.
Kozdrój, J., Frączek, K., Ropek, D., 2019. Assessment of bioaerosols in indoor air of glasshouses located in a botanical garden. Build. Environ. 166, 106436.
Kritana, P., Taehyeung, K., Hyeontae, K., Ki Youn, K., Wongeun, S., 2014. Atmospheric pathway: a possibility of continuous outbreaks of foot-and-mouth disease in South Korea in 2010–2011. Comput. Electron. Agr. 108, 95–104.
Li, T., Zhou, X.C., Ikhumhen, H.O., Difei, A., 2018. Research on the optimization of air quality monitoring station layout based on spatial grid statistical analysis method. Environ. Technol. 39 (10), 1271–1283.
Li, X., Hu, X., Shi, S., Shen, L., Luan, L., Ma, Y., 2019. Spatiotemporal variations and regional transport of air pollutants in two urban agglomerations in Northeast China Plain. Chin. Geogr. Sci. 29 (6), 917–933.
Li, X., Hussain, S.A., Sobri, S., Md Said, M.S., 2021. Overviewing the air quality models on air pollution in Sichuan Basin, China. Chemosphere 271, 129502.
Madhwal, S., Prabhu, V., Sundriyal, S., Shridhar, V., 2020. Distribution, characterization and health risk assessment of size fractionated bioaerosols at an open landfill site in Dehradun, India. Atmos. Pollut. Res. 11 (1), 156–169.
Maheswaran, D., Zeng, Y., Chan-Yeung, M., Scott, J., Osornio-Vargas, A., Becker, A.B., Kozyrskyj, A.L., 2014. Exposure to Beta-(1,3)-D-glucan in house dust at age 7–10 is associated with airway hyperresponsiveness and atopic asthma by age 11–14. PLOS ONE 9 (6), e98878.
Morakinyo, O.M., Mokgobu, M.I., Mukhola, M.S., Hunter, R.P., 2016. Health outcomes of exposure to biological and chemical components of inhalable and respirable particulate matter. Int. J. Environ. Res. Public Health 13 (6), 592.
Nag, R., Monahan, C., Whyte, P., Markey, B.K., O'Flaherty, V., Bolton, D., Fenton, O., Richards, K.G., Cummins, E., 2021. Risk assessment of Escherichia coli in bioaerosols generated following land application of farmyard slurry. Sci. Total Environ. 791, 148189.
Oh, H.J., Ma, Y., Kim, J., 2020. Human inhalation exposure to aerosol and health effect: aerosol monitoring and modelling regional deposited doses. Int. J. Environ. Res. Public Health 17 (6), 1923.
Pappas, G., 2022. The Lanzhou Brucella leak: the largest laboratory accident in the history of infectious diseases? Clin. Infect. Dis. 75 (10), 1845–1847.
Rahman, S.M.T., Kabir, A., 2019. Factors influencing location choice and cluster pattern of manufacturing small and medium enterprises in cities: evidence from Khulna City of Bangladesh. J. Glob. Entrep. Res. 9 (1), 61.
Roghani, A., Panahi, S., 2021. The Global Distribution of COVID-19 Vaccine: The Role of Macro-socioeconomics Measures. medRxiv (in Chinese).

Rzeszutek, M., 2019. Parameterization and evaluation of the CALMET/CALPUFF model system in near-field and complex terrain - terrain data, grid resolution and terrain adjustment method. Sci. Total Environ. 689, 31–46.

Singh, N.K., Sanghvi, G., Yadav, M., Padhiyar, H., Thanki, A., 2021. A state-of-the-art review on WWTP associated bioaerosols: microbial diversity, potential emission stages, dispersion factors, and control strategies. J. Hazard. Mater. 410, 124686.

Tuon, F.F., Gondolfo, R.B., Cerchiari, N., 2017. Human-to-human transmission of Brucella – a systematic review. Trop.Med. Int. Health 22 (5), 539–546.

Van Leuken, J.P.G., Swart, A.N., Havelaar, A.H., Van Pul, A., Van der Hoek, W., Heederik, D., 2016. Atmospheric dispersion modelling of bioaerosols that are pathogenic to humans and livestock – a review to inform risk assessment studies. Microb. Risk. Anal. 1, 19–39.

Walser, S.M., Gerstner, D.G., Brenner, B., Bünger, J., Eikmann, T., Janssen, B., Kolb, S., Kolk, A., Nowak, D., Raulf, M., Sagunski, H., Sedlmaier, N., Suchenwirth, R., Wiesmüller, G., Wollin, K.-M., Tesseraux, I., Herr, C.E.W., 2015. Evaluation of exposure–response relationships for health effects of microbial bioaerosols – a systematic review. Int. J. Hyg. Environ. Health 218 (7), 577–589.

Wouters, O.J., Shadlen, K.C., Salcher-Konrad, M., Pollard, A.J., Larson, H.J., Teerawattananon, Y., Jit, M., 2021. Challenges in ensuring global access to COVID-19 vaccines: production, affordability, allocation, and deployment. Lancet 397 (10278), 1023–1034.

Wu, S., Wang, Y., Chen, C., Cao, Z., Cao, J., Yu, Z., Song, H., 2021. Valley city ventilation under the calm and stable weather conditions: a review. Build. Environ. 194, 107668.

Xu, Z., Yao, M., 2013. Monitoring of bioaerosol inhalation risks in different environments using a six-stage Andersen sampler and the PCR-DGGE method. Environ. Monit. Assess. 185 (5), 3993–4003.

Xu, Y., Xue, W., Lei, Y., Huang, Q., Zhao, Y., Cheng, S., Ren, Z., Wang, J., 2020. Spatiotemporal variation in the impact of meteorological conditions on PM2.5 pollution in China from 2000 to 2017. Atmos. Environ. 223, 117215.

Yuan, Wen-yan, W. P., Bo, Xin, Guo, Jing, Yang, Zhao-xu, Xue, Xiao-da, Chang, Xiang-yu, Zhang, Jin-liang, Tian, Jun, Wang, Gang, Ma, Yan, 2020. The potential impact of bioaerosol emissions on human health threats. China Environ. Sci. 40 (7), 3173–3178 (in Chinese).

Zhao, Y., Chen, Z., Hou, J., Mao, D., Lin, H., Xue, Y., Luo, Y., 2020. Monitoring antibiotic resistomes and bacterial microbiomes in the aerosols from fine, hazy, and dusty weather in Tianjin, China using a developed high-volume tandem liquid impinging sampler. Sci. Total Environ. 731, 139242.