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Worker exposure to bioaerosols from sludge dewatering facilities: risks and mitigations

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Abstract

Sludge dewatering process is a major source of bioaerosols in wastewater treatment plants (WWTPs) which can pose significant health risks to on-site workers. While quantitative microbial risk assessment (QMRA) is commonly performed to assess the human health risks, it lacks immediacy in determining on-site risk levels. Alternatively, comparing detected concentrations of bioaerosols with critical concentration standards provides a practical approach. This study investigates *E. coli* bioaerosol emissions from a sludge dewatering process (or facility) in a municipal WWTP under different working postures, ventilation scenarios, and seasonal conditions. The objective was to estimate a ceiling-type exposure limit (EL) corresponding to acceptable risk levels using Monte Carlo simulation and reverse QMRA. Sensitivity analysis was also used to identify the key input parameters significantly affecting the risk exposure. Results showed that the bioaerosol concentration in poor ventilation was 1.6–1.7 times as large as that in natural ventilation. The respirable fractions (particle size < 4.7 μm) accounted for 78%–100% of the total bioaerosol emissions. Opening the windows increased the EL up to 1.6 times higher compared to closed-window conditions under the optimistic scenario. Wearing masks reduced significantly the fraction of bioaerosols inhaled by workers, resulting in derived EL that were one to two orders of magnitude higher (2.24 – 20.10 CFU/m^3) than those estimated without masks (0.09 – 0.41 CFU/m^3). Among all parameters, the removal of the respirable fraction by the masks was the dominant contributor to EL estimation. EL benchmarks also varied with seasonal conditions and working postures. Overall, this study provides novel quantitative insights for deriving occupational exposure limits for bioaerosol exposure in dewatering facilities.

Keywords: Wastewater treatment plants; Bioaerosols exposure; Reverse quantitative microbial risk assessment; Acceptable exposure concentration

1 Introduction

The substantial growth in urbanization and economic development has led to a significant rise in the number of wastewater treatment plants (WWTPs) (Bairoliya and Miller, 2021; Han et al., 2020; Wang et al., 2022). This increase has resulted in a notable accumulation of residual sludge, a by-product of wastewater treatment, that needs to be dewatered to manage the mounting volume of collected sludge (Sun et al., 2022; Zhang et al., 2022). During the dewatering process, pathogenic microorganisms present in the sludge are released into the air as bioaerosols due to disturbances of dewatering facilities and splashing droplets (Fathi et al., 2017; Katsivela et al., 2017; Xu et al., 2018). Specifically, indoor sludge dewatering processes are one of the most significant and main sources of bioaerosols in WWTPs (Han et al., 2018; Xu et al., 2020; Yang et al., 2019). The confined environment of dewatering facilities contributes to the accumulation of high concentrations of bioaerosols as the structure of the roofs and the internal walls impede their dispersion. Further to this, factors such as limited exposure to solar radiation and inadequate ventilation exacerbate the build-up of bioaerosols within these indoor spaces (Gollakota et al., 2021; Han et al., 2019; Xu et al., 2018). Yang et al. (2019) and Denpetkul et al. (2022) reported the quality of ventilation and seasonal changes significantly impact the emission of bioaerosols from indoor dewatering facilities. In addition, Zhong et al. (2016) showed that the composition of airborne bacteria is influenced by seasonal variations. Indoor dewatering facilities can pose a high-health-risk built environment due to the potential negative impacts of bioaerosols on human health, such as Sick Building Syndrome and Sewage Workers' Syndrome (Kumar et al., 2021; Mbareche et al., 2022; Szulc et al., 2021). Thus, systematic investigation into the presence of pathogenic bioaerosols is necessary (Korzeniewska, 2011; Li et al., 2022; Xu et al., 2020). *Escherichia coli*

78 (*E. coli*) is a gram-negative enteric bacterium commonly used as an indicator of fecal
79 contamination in environmental and occupational settings (Adhikari et al., 2020;
80 Keithlin et al., 2014). Although most strains are harmless commensals, the species
81 include pathogenic variants such as *E. coli* O157:H7 that can cause severe disease,
82 underscoring the importance of assessing *E. coli*–containing bioaerosols in exposure
83 and risk evaluations. (de Matos Nascimento et al., 2020).
84 According to Wang et al. (2022), regular exposure to *E. coli* bioaerosols can lead to
85 respiratory infections and other health complications. Studies in wastewater treatment
86 plants (WWTPs) have consistently reported the predominance of *E. coli* bioaerosols,
87 which have been associated with symptoms such as general malaise, weakness, acute
88 rhinitis, and fever (Mbareche et al., 2022; Kataki et al., 2022; Heinonen-Tanski et al.,
89 2009; Lou et al., 2021; Szulc et al., 2021). Because pathogenicity varies among
90 strains, several studies have used *E. coli* O157 as a reference pathogen, estimating its
91 concentration as a fraction (e.g., 8%) of total *E. coli* (Haas et al., 2000; Howard et al.,
92 2006; Nguyen-Viet, 2014; Riley, 1983; Kouamé et al., 2017). This strain was
93 identified in the 1980s as a major cause of diarrheal outbreaks in the United States,
94 establishing it as a classical indicator of fecal contamination.
95 For on-site workers, inhalation is the primary exposure pathway (Han et al., 2020;
96 Hsiao et al., 2020; Wang et al., 2022). Thus, the respirable fraction of aerosolized *E.*
97 *coli*, particles smaller than 4.7 μm capable of reaching the lower respiratory tract, is of
98 greatest concern (Ghosh et al., 2013; Han et al., 2019). This threshold follows the
99 Andersen six-stage cascade impactor classification, where particles ≤ 4.7 μm
100 collected in stages 3–6 define the respirable fraction (Andersen, 1958).
101 Occupational health risks can be assessed by comparing on-site *E. coli* concentrations
102 with site-specific exposure limits (ELs) derived from critical concentration

calculations (Li et al., 2013; Lu et al., 2020). These ELs serve as ceiling limits, representing maximum allowable bioaerosol concentrations that should not be exceeded to prevent unacceptable health risks (Lu et al., 2020; Mbareche et al., 2019). Such benchmarks provide practical guidance for on-site risk assessment and inform mitigation strategies to reduce bioaerosol exposure (Dean and Mitchell, 2020; Rasheduzzaman et al., 2019). In this study, the term EL refers to a probabilistically derived, ceiling-type benchmark obtained via reverse quantitative microbial risk assessment (reverse-QMRA), rather than an ACGIH-defined threshold limit value. Ghosh et al. (2015) pointed out the need to estimate ELs for diverse airborne microorganisms across indoor environments to evaluate associated health risks (Tsai and Liu, 2009). Similarly, Gorny and Dutkiewicz, (2002) emphasized the utility of critical concentration of bioaerosols in protecting exposed individuals (Gollakota et al., 2021). Various organizations have proposed ELs for airborne bacterial concentrations in indoor residential, office, and non-industrial workplace environments, typically ranging from 500 CFU/m^3 to 5×10^3 CFU/m^3 (Gorny and Dutkiewicz, 2002; Organization, 1990; Organization, 2002; Otten et al., 1986). For example, the WHO recommends 500 CFU/m^3 as a critical total bacterial concentration, while some countries adopt different thresholds Korea (800 CFU/m^3), Finland (4.5×10^3 CFU/m^3), and the Netherlands and Germany (1×10^4 CFU/m^3) (Ghosh et al., 2015; Jo and Kang, 2006; Organization, 1990). However, these ELs primarily target residential and office environments, and no specific benchmarks currently exist for industrial built environments such as dewatering facilities (Lim et al., 2015; Mbareche et al., 2022).

ELs for bioaerosols are typically derived using reverse-QMRA frameworks, guided by authoritative targets from the WHO and U.S. EPA (Hamilton et al., 2019; Lu et al.,

2020; Shoults et al., 2021), including an acceptable annual infection risk (10^{-4} per person per year) and a disease burden (10^{-6} DALYs per person per year) (Kataki et al., 2022). Reverse-QMRA has previously been applied to estimate human exposure to pathogens such as *Salmonella enterica* and *E. coli* in recreational freshwater settings (Soller et al., 2010), and to establish critical concentrations for *Legionella pneumophila* in various indoor and outdoor environments (Hamilton et al., 2019; Shoults et al., 2021) as well as *Pseudomonas aeruginosa* in plumbing systems (Dean and Mitchell, 2020). More recently, QMRA-based risk calculators have been developed to estimate infection risks for wastewater treatment plant workers across multiple pathogens, exposure routes, and job tasks, providing a practical framework for occupational risk management (Heida et al., 2024).

The present study focuses on deriving task-specific EL benchmarks for culturable airborne *E. coli* O157 using a simplified reverse-QMRA approach. We investigated *E. coli* aerosolization during the dewatering process in a municipal WWTP, including the concentration, size, and distribution of airborne bacteria. Variations in working posture (stooping vs. standing) and ventilation (windows closed vs. open) were considered across spring and summer seasons. The resulting EL benchmarks represent ceiling-type limits for occupational exposure, derived from measured airborne E. coli concentrations (CFU/m³) rather than heterotrophic plate counts (HPC) or total viable cell counts. Sensitivity analysis was conducted to identify the most influential parameters affecting bioaerosol emission and worker exposure, ensuring the derived ELs provide practical guidance for risk assessment and mitigation in industrial environments.

2 Method and materials

2.1 Sampling and analysis

[Fig. 1 inserts here]

Bioaerosols (culturable *E. coli*) measurements were carried out at the dewatering facility of a municipal WWTP located in the central part of P.R. China (Fig. 1). The WWTP, which was built in 2014, has two parallel treatment lines, and has a daily treatment capacity of 50,000 m^3/day. Throughout the wastewater treatment process, sludge gradually accumulates in the secondary sedimentation tank. The primary treatment involves gravity thickening to reduce water content in the residual sludge. The secondary treatment involves the addition of chemical flocculation for sludge conditioning to promote the aggregation of sludge flocs and further increase the particle size. Centrifugation is then applied for further sludge dewatering and reduction the sludge volume. The dewatered sludge is then transported off-site for subsequent treatment and disposal. The daily sludge production is 400 t/day (wet sludge) and remains unchanged during this study. Additional information on the dimensions and operational performance of the dewatering facility are provided in Supplementary Material (Table S1).

The doors of the dewatering facility are always closed. The poor and natural ventilation scenarios corresponded to closed and opened windows, respectively (Supplementary Material Fig. S1). The dewatering facility is equipped with 4 parallel centrifuges, which can reduce sludge water content from 95% to 78%. The four centrifuges operated continuously during the four days of independent sampling campaigns in 2022 (28th March, 1st April, 16th June, and 27th June). Details on the seasons and weather conditions during the sampling campaigns are provided in

Supplementary Material (Table S2). Three Andersen six-stage Cascade impactor (FA-1, Hongchangxin Inc., Beijing, China) with a flow rate of 28.3 L/min were used simultaneously for bioaerosol particle collection for 20 minutes (Hung et al., 2010). The sampling point was next to the parallel centrifuges (Fig. 1). Based on the sampling flow rate and duration, the total sampled air volume was 0.566 m^3, resulting in a limit of detection of approximately 1.8 CFU/m^3, corresponding to the detection of a single colony after positive-hole correction. The impactor collects and aerodynamically sizes the particles by inertially impacting them onto agar plates at 6 stages: stage 1 (> 7 μm), stage 2 (4.7 –7 μm), stage 3 (3.3 –4.7 μm), stage 4 (2.1 –3.3 μm), stage 5 (1.1 –2.1 μm) and stage 6 (0.65 –1.1 μm) (Xu et al., 2018). Analysis for airborne culturable *E. coli* was done on the *E. coli* selective agar medium in accordance with the standard procedure and formula (Frampton and Restaino, 1993; Frampton et al., 1988; Kilian and Bülow, 1979; Manafi, 1996). Before the sampling campaigns, the medium was prepared in a 90 mm petri plates and the impactor was loaded with six petri plates to enumerate *E. coli*. The sampling heights were 1.2 and 1.5 m according to the exposure scenarios of stooping and standing working postures, respectively. The impactor was sterilized with 75% ethanol before each sampling. After sampling, the plates were sealed and transported immediately to the laboratory in ice boxes with ice (Han et al., 2019), and the plates were incubated in a constant-temperature incubator at 37 °C for 24 h (Bragoszewska and Biedron, 2018; Pascual et al., 2003). Dark purple colonies were identified as *E. coli* based on morphology (Frampton et al., 1988; Kilian and Bülow, 1979; Bragoszewska and Biedron, 2018; Pascual et al., 2003). Confirmation was performed using the indole test, in which a drop of 4-(dimethylamino)benzaldehyde and hydrochloric acid in n-butanol was applied to the colonies (Blood and Curtis, 1995; Manios and Skandamis, 2015). A

positive reaction was indicated by the formation of a cherry-red color (Lombard and Dowell Jr, 1983). Enumeration of bioaerosol colonies (CFU) was conducted using an automatic colony counting instrument. Enumeration of the sample colonies (CFU) of bioaerosols was undertaken using an automatic colony enumeration instrument (HICC-B, Wanshen Inc., Hangzhou, China) (Hung et al., 2010). The positive-hole correction method was adopted to correct colony counts (Supplementary Material Eq. (1)) (Andersen, 1958; Han et al., 2019; Xu et al., 2018). Sample concentrations were calculated and expressed as CFU/m^3 as described in Supplementary Material (Eq. (2)). The ratio of particle size distribution of bioaerosols was calculated using Supplementary Material Eq. (3). Quality control procedures were implemented during both field sampling and laboratory analysis. Negative controls were used to assess potential contamination, and laboratory positive controls using reference *E. coli* cultures were applied to verify media performance and incubation conditions (Heijnen and Medema, 2006).

2.2 Reverse-QMRA

The classical four-step reverse-QMRA framework, namely, hazard identification, exposure assessment, dose–response model, and risk characterization, was used to assess the EL benchmarks (Stellacci et al., 2010). For hazard identification, *E. coli* was selected as the main pathogen of concern (Lou et al., 2021; Nag et al., 2021). Risk characterization was carried out based on two widely used risk targets commonly applied in QMRA: the U.S. EPA annual infection risk (10^{-4} per person per year) (Supplementary Material Eq. 4) and WHO disease burden (10^{-6} DALYs per person per year) (Supplementary Material Eqs. 5 and 6) (Haas et al., 2014; Pasalari et al., 2019). For each exposure scenario, the exposure route of pathogenic *E. coli*

bioaerosols was unintentional inhalation during routine occupational activities (Mbanga et al., 2020; Shi et al., 2018). The dose–response model of beta-Poisson was used to determine the acceptable exposure dose grounded on inhalation exposure route based on Supplementary Material (Eqs. 7 and 8) (Pasalari et al., 2019). Moreover, the analytical QMRA framework developed by (Haas et al., 2014) has been widely applied for evaluating human health risks from bioaerosol exposure because it provides well-established dose–response models and parameter values that represent human infection processes. In many previous QMRA studies of occupational bioaerosol exposure, the average exposure dose has been used as the basis for dose–response assessment (Shi et al., 2018). However, inhaled bioaerosols must be transported and deposited within specific regions of the respiratory tract for infection to occur, and losses during this process are not explicitly captured by average exposure dose alone (Hamilton et al., 2017; Huang and Haas, 2009).

The QMRA framework of Hamilton et al., (2017) was adopted to account for these processes by coupling inhalation exposure with potential gastrointestinal infection resulting from swallowing particles deposited in the nasopharyngeal region. This approach improves the biological relevance of the dose–response assessment and supports the selection of model parameters used in the Monte Carlo simulations (Huang et al., 2010). The bioaerosol respirable ratio (IR) was calculated using Eq. (9) in the Supplementary Material. It was defined as the ratio between the sample concentrations collected in the stages 3–6 and 1–6 of the Andersen six-stage cascade impactor (Table 2). Tables 1 and 2 display the exposure scenarios and parameters used in the assessment, respectively. The exposure time reported in Table 1 represents task-based time spent near operating centrifuges under specific working postures, rather than a complete 8-h work shift, as workers rotate between tasks and locations within

252 the dewatering facility. Breathing rate values were adopted from standard
253 occupational exposure factor data reported by (Duan, 2013), which are commonly
254 used in QMRA studies. The following assumptions were taken for the reverse-
255 QMRA: (i) total culturable *E. coli* concentrations were used as the exposure metric.
256 Pathogenic *E. coli* exposure was represented using *E. coli* O157 as a reference strain,
257 with its concentration estimated as a fixed fraction of total *E. coli* based on
258 established QMRA practice and published literature, in the absence of site-specific
259 pathogen occurrence data (Haas et al., 2000; Howard et al., 2006; Nguyen-Viet,
260 2014).(O'Toole et al., 2012); (ii) a microorganism could pose health risks if it reaches
261 an appropriate location, and that microorganisms have an equal and independent
262 probability of survival and causing infection upon reaching a location for the beta-
263 Poisson dose–response model (Hamilton et al., 2017; Petterson and Ashbolt, 2003);
264 and (iii) the term "personal protective equipment" (PPE) referred to a range of masks
265 with filter efficiency between N-95 and N-99: PPE removal efficiency was applied as
266 a particle size-dependent filtration assumption rather than a pathogen-specific
267 removal mechanism (Locke et al., 2021; Organization, 2020). The dose–response
268 relationship, disability-adjusted life year (*DALY* per case), and $P_{ill|inf}$ values applied in
269 the reverse-QMRA framework correspond specifically to pathogenic *E. coli* O157 and
270 are based on human health risk models for inhalation exposure with subsequent
271 ingestion via the nasopharyngeal route, ensuring consistency between exposure
272 assessment and health risk characterization (Esfahanian et al., 2019; Gibney et al.,
273 2013; Keithlin et al., 2014; Rasheduzzaman et al., 2019).
274 The term exposure limit (EL) is used as a probabilistically derived exposure
275 benchmark rather than an occupational exposure limit defined by the American
276 Conference of Governmental Industrial Hygienistsre. The EL is interpreted as a

277 ceiling-type reference concentration that should not be exceeded during sludge
278 dewatering operations. Because exposure concentrations are estimated using Monte
279 Carlo simulation, the resulting ELs form a distribution rather than a single
280 deterministic value. Different percentiles of this distribution may be selected
281 depending on risk tolerance and policy objectives. In this work, the 97.5th percentile
282 is adopted as a health-protective ceiling limit under optimistic exposure conditions,
283 while lower percentiles represent more conservative, worst-case exposure scenarios
284 (Noppakuadrittidej et al., 2025).
285
286 [Table 1 inserts here]
287 [Table 2 inserts here]

288 **2.3 Monte Carlo simulation and sensitivity analysis**

289 EL benchmarks were determined through 10,000 iterations using Crystal Ball and
290 Microsoft Excel 2013 (Buonanno et al., 2020). All inputted parameters exposure time
291 (T), bioaerosol respirable ratio (IR), and removal fraction by employing personal
292 protective equipment (F_{PPE}) were randomly selected from their corresponding
293 probability distributions (Table 1 and 2). The outputs of Monte Carlo distribution
294 were displayed using a chart with box and whiskers. The lower and upper whisker
295 represent the 2.5th (conservative estimate in the worst-case condition) and 97.5th
296 (optimistic estimate in the best-case condition) percentile quantiles (Haas et al., 2017).
297 The ceiling limit is the upper whisker which represents 97.5th percentile quantile.
298 Sensitivity analysis using the Spearman-rank correlation coefficient was conducted to
299 quantify the influence of each input parameters on the uncertainty of the output
300 parameter (Dean and Mitchell, 2020; Dias et al., 2019; Saltelli et al., 2019). Higher
301 absolute ranking values indicate great contribution and impact on the variability of the

EL benchmark (Pang et al., 2017; Pasalari et al., 2019). To assess their relative importance, the contribution to variance was calculated by squaring the rank correlation coefficient and normalizing it to 100% (Shi et al., 2018; Zhou et al., 2014). The sensitivity level ranged from 0% to 100% denoting the percentage of the variance of the predicted variable contributed by each input parameter to each predicted variable (Haas et al., 2017; Shi et al., 2018).

3 Results and discussion

3.1 Emission characteristics

3.1.1 Bioaerosol sample concentration

The exposure levels of aerosolized *E. coli* concentrations to workers considering their working postures and seasonal conditions are shown in Figure 2. The underpinning data are provided in Supplementary Material (Table S3). In the spring period, the mean concentrations of bioaerosols ranged between 23 and 41 CFU/m^3. In the poor-ventilation scenario (closed window), mean concentrations were 1.6 and 1.7 times higher compared to those in the natural-ventilation scenario (open window) during stooping and standing working postures, respectively.

[Fig. 2 inserts here]

This result was expected as natural ventilation promotes air exchange between indoor and outdoor environment due to pressure difference created by wind passing through the windows which in turn dilutes the bioaerosols concentrations (Ding et al., 2016; Gollakota et al., 2021; Xu et al., 2020).

During the spring season, under poor and natural ventilation conditions, the mean *E.*

coli concentrations under stooping posture were 1.1 and 1.2 times higher than standing posture, respectively. This was due to the gravitational settling of larger bioaerosol particles and localized emission and dilution effects near the source, which together result in higher measured concentrations at lower working heights (De Oliveira et al., 2021; Schreck et al., 2021). Similarly, Song, (2020) observed a correlation between lower height and higher bioaerosols concentrations with levels reported at 889 CFU/m^3 at 0.1 m, 867 CFU/m^3 at 0.5 m, and 625 CFU/m^3 at height 1.2 m.

During the summer period, a comparable pattern was noted, except in the case of the stooping working posture, where the mean *E. coli* concentration in the poor-ventilation scenario was 0.5 times higher than in the natural-ventilation scenario. Moreover, in the poor-ventilation scenario, the mean concentration under the stooping working posture was 0.44 times larger than under the standing working posture. These differences were likely influenced by environmental factors such as temperature and relative humidity (Law et al., 2001; Xu et al., 2020). The closed window conditions during summer consistently showed higher temperatures and lower relative humidity under the stooping working posture compared to the standing posture (Supplementary Material Table 2). Elevated temperature and decreased humidity levels were unfavorable for the survival of bioaerosols. Previous studies have also supported these findings (Gollakota et al., 2021; Han et al., 2019). Additionally, Law et al. (2001) observed a strong positive correlation between indoor relative humidity levels and bioaerosol concentration in investigated offices, indicating an exponential increase in bioaerosol concentration with higher average relative humidity.

Typically, during the summer period, the mean *E. coli* concentration was 1.1–1.7 times higher compared to the spring period, except for the scenario involving workers

352 in a stooping posture with closed windows during the summer. This finding is in good
353 agreement with Lee et al. (2021), who observed significantly high levels of airborne
354 bacterial concentrations in various indoor settings across public facilities and
355 buildings in the Republic of Korea during the summer season. Similarly, Han et al.
356 (2018) noted seasonal variations in airborne cultivable bacteria levels in an indoor
357 sludge dewatering facility, with the highest concentrations recorded during the
358 summer. Although seasonal differences in *E. coli* bioaerosol concentrations were
359 observed, these results should be interpreted with caution (Frankel et al., 2012). The
360 sampling campaign was conducted over four individual days across two seasons
361 (spring and summer), which limits the ability to capture intra-seasonal variability and
362 longer-term temporal trends fully. Therefore, the observed differences reflect
363 conditions during the specific sampling periods rather than comprehensive seasonal
364 patterns. Extended monitoring with higher temporal resolution across all seasons
365 would be required to characterize seasonal variability in occupational bioaerosol
366 exposure robustly. Air exchange rates (ACH) were not directly measured in this study;
367 therefore, ventilation was characterized qualitatively based on window status (open
368 vs. closed), which reflects practical operational conditions but limits direct
369 comparison with ACH-based studies (Memarzadeh and Xu, 2012).

370 Conversely, the non-detect samples were excluded when calculating averages and
371 standard deviations to reflect a worst-case scenario (Lubin et al., 2004). While this
372 approach introduces bias and may generate artificially high values based on arbitrary
373 decisions, it is often considered preferable to omitting risk assessment entirely. Even a
374 conservative, overestimated result can be acceptable for stakeholders prioritizing
375 health risk mitigation (Programs, 2000). Moreover, given the critical, costly, and high-
376 stakes nature of environmental health risk decisions, this method is straightforward

and inexpensive, and substitution of a few values is unlikely to substantially distort the overall results (Helsel, 2005).

3.1.2 Particle size distribution

For all exposure scenarios, the *E. coli* bioaerosol respirable fractions, ranging from 0.65 μm to 4.7 μm (Andersen stages 3-6) represented between 78% and 100% of the total particles (Fig. 3). Typically, the particle size distribution peak was observed within the 1.1–4.7 μm range (stages 5 and 6). This tendency is attributed to the high-speed rotation of sludge dewatering centrifuges, which tends to break down bioaerosol particles into smaller fractions Vestlund et al. (2014). Although impaction-based sampling with an Andersen cascade impactor may reduce microbial viability due to mechanical stress, it is widely used and provides a consistent basis for comparative particle size distribution analysis across exposure scenarios.

[Fig. 3 inserts here]

During spring or summer, the respirable fractions of *E. coli* bioaerosols were up to 1.1 times higher in the poor ventilation scenario compared to the natural ventilation setting. Higher concentration in the poor ventilation scenario compared to the natural ventilation are likely due to the accumulation of bioaerosols during poor ventilation and the dilution effect in natural ventilation (open window) (Yang et al., 2019). In this study, poor and natural ventilation scenarios are used to represent relative differences in air exchange rate, rather than window status alone. Natural ventilation (open windows) corresponds to higher air exchange and enhanced dilution of airborne particles, whereas poor ventilation (closed windows) reflects lower air exchange and

particle accumulation. Although air exchange is commonly expressed as air changes per hour (ACH), ACH was not quantified in this study because airflow rate and opening velocity were not measured. Therefore, ventilation effects on particle size distribution are interpreted qualitatively in terms of lower versus higher air exchange (Memarzadeh and Xu, 2012). Guo et al. (2014) supported this finding, observing a reduction of over 60% in airborne bacterial colonies emitted from a sludge treatment system after several hours of natural ventilation. Under different working postures, the proportion of *E. coli* bioaerosol respirable fractions ranged between 78% and 100% for stooping and 82% and 98% for standing positions. Across seasons, the proportion of *E. coli* bioaerosol respirable fractions in summer (90%–100%) consistently exceeded that in spring (78%–92%) in the same ventilated environment. Moreover, the summer proportion was 1.1–1.3 times higher than that in spring, attributed to the elevated temperature in summer positively influencing the smaller size of bioaerosol particles (Supplementary Material Table 2). Guzman, (2021) supported this observation, showing that higher temperature caused bioaerosol particle size reduction, increasing the proportion of respirable fractions by 2.4 times.

3.2 Exposure limit of critical concentration

The EL benchmarks of acceptable exposure concentrations for exposure to *E. coli* bioaerosols under the stooping and standing working postures in different season periods are provided in Fig. 4 and 5. These benchmarks reflect different modeling assumptions, with lower percentiles representing conservative worst-case conditions and upper percentiles representing optimistic best-case conditions. Detailed EL benchmarks of acceptable exposure concentrations are provided in Supplementary Material (Table S5 and S6).

In spring, the *E. coli* bioaerosol EL benchmarks ranged from 0.09 to 20.10 CFU/m^3 with in natural ventilation scenarios. These were 1 and 1.6 times higher than the poor ventilation scenariosunder the optimistic estimate (0.09–15.70 CFU/m^3; Fig. 4a and Supplementary Material Table S5).

[Fig. 4 inserts here]

Thus, maintaining ventilation can lead to a more favorable health risk assessment outcome (Li Y.J et al., 2021). Núñez and García, (2022) previously argued that natural ventilation through windows is a critical strategy to reduce bioaerosol infection risks, especially in indoor environments during warm seasons. Moreover, the field sampling campaign revealed that working posture impacted bioaerosol emission characteristics and particle size distribution, consistently resulting in higher calculated IR, when workers are standing up compared to stooping posture (Table 2). Additionally, wearing a mask substantially improved the *E. coli* bioaerosol EL benchmark by two orders of magnitude compared to not wearing a mask under the optimistic estimate (Fig. 4a and Supplementary Material Table 5). This result is in good agreement with Lee et al. (2021) and Zaneti et al. (2021), demonstrating that PPE like masks effectively blocks bioaerosol particles, significantly mitigating the health risks associated with exposure to these particles. Furthermore, the *E. coli* bioaerosol EL benchmarks for female exposure populations were 1.3 times larger than those for males under the optimistic estimate. This difference stemmed from the higher breathing rate for males compared to females (Table 2), despite the inverse relationship between EL and the inputted breathing rate in reverse-QMRA (Supplementary Material Eq. (10)). This aligns with findings from Xu et al. (2020)

and Li et al. (2022), demonstrating a higher health risk of infection and disease in men than in women during their exposure to airborne pathogenic microorganisms in a municipal sludge treatment plant. Similar findings were observed in the summer period, although opposite conclusions were drawn under different working postures. Under the standing working posture (0.10–24.20 CFU/m^3), the calculated *E. coli* bioaerosol EL benchmark was at least between 1 and 1.6 times larger than the conservative estimates worst-case condition and the optimistic estimates best-case condition under the stooping working posture (0.10–16.80 CFU/m^3), respectively (Fig. 4b and Supplementary Material Table 5).

[Fig. 5 inserts here]

This discrepancy was influenced by the respirable fraction of bioaerosols, which was impacted by changes in temperature and humidity during spring and summer (Ahlawat et al., 2020; Guzman, 2021). Furthermore, similar results were obtained based on the WHO disease burden risk level (Fig. 5 and Supplementary Material Table 6).

Although there is not an international exposure limits standard for airborne microorganisms in indoor environments, several recommendations have been proposed to control indoor microbiological contamination (Lim et al., 2015; Mbareche et al., 2019). The guideline of Andualem et al. (2019) proposed a exposure limit below 4500 CFU/m^3 for indoor bacterial bioaerosols. The WHO recommends a limit of 500 CFU/m^3 for the total airborne bacteria in indoor workspaces (Organization, 1990; Organization, 2002). Meanwhile, the European Union recommends 2000 CFU/m^3 for non-industrial indoor locations and 10000 CFU/m^3 for

476 private homes (Wanner, 1994). Heida et al. (1995) reported that airborne bacterial
477 concentrations above 10^4 CFU/m^3 should be considered a health threat. In this study,
478 the ELs ranged between 0.02 and 24.20 CFU/m^3, significantly lower than the
479 aforementioned standard values.

480 Several uncertainties inherent to the reverse-QMRA framework must be
481 acknowledged. Health risks from pathogenic *E. coli* are often dominated by *E. coli*
482 O157 due to its severe clinical outcomes, making it a widely accepted reference
483 pathogen in QMRA studies (Haas et al., 2014; Howard et al., 2006; Nguyen-Viet,
484 2014). Although pathogenic *E. coli* includes multiple strains with varying virulence
485 and dose–response characteristics (Haas et al., 2000; Teunis et al., 2004), using O157
486 as a reference represents a conservative, health-protective assumption aligned with
487 simplified QMRA practice and regulatory reliance on *E. coli* as a fecal indicator.
488 Therefore, the derived EL benchmarks should be viewed as conservative exposure
489 limits, not precise strain-specific risk estimates. Regarding risk targets, the annual
490 infection risk of 10^{-4} per person per year has primarily been applied in drinking water
491 and water reuse assessments, and its direct relevance to airborne occupational
492 exposure is less certain (Leandro et al., 2022). In contrast, the DALY-based target
493 offers a more generalizable health metric across exposure routes (Gibney et al., 2013).
494 This study applied both targets to generate complementary, conservative EL
495 benchmarks, which should be interpreted within these contextual limitations.

496 **3.3 Sensitivity analysis**

497 Among all variables, removal fraction by equipping personal protective equipment
498 (F_{PPE}) consistently showed the highest sensitivity, ranging from 0.72 to 0.90 (Fig. 6)
499 and contributing 23% to 31% to the exposure limit (EL) benchmark (Fig. 7). Notably,
500 the sensitivity level for F_{PPE} was up to 3.5 and 9 times higher compared to T and IR,

501 respectively (Fig. 6). This highlights the importance of wearing PPE in reducing
502 effective worker exposure, thereby increasing the derived EL benchmark and
503 lowering occupational health risk. This further supports previous studies endorsing the
504 effectiveness and simplicity of PPE as an intervention to mitigate health risks in daily
505 routines (Carducci et al., 2018; Haas et al., 2017; Liu and Zhao, 2021).
506 However, the assumed F_{PPE} values correspond to certified N95–N99 filtration
507 efficiencies and therefore represent ideal or near-ideal respirator performance. In real
508 working environments, the effective removal efficiency may be reduced due to
509 improper fit, facial movement during physical activity, prolonged usage, or moisture
510 accumulation caused by high humidity and perspiration in dewatering facilities
511 (Gautam et al., 2021). These factors may lead to lower actual protection levels than
512 those assumed in the model. Consequently, the derived EL benchmarks should be
513 interpreted as upper-bound estimates under well-managed PPE usage, emphasizing
514 the need for proper fit testing, routine replacement, and integration with engineering
515 controls such as ventilation.
516 [Fig. 6 inserts here]
517 [Fig. 7 inserts here]
518
519 The contribution of input parameters, bioaerosol respirable ratio (IR), and exposure
520 time (T) to the EL benchmark ranked second or third most important parameters. As
521 defined in the reverse-QMRA framework, IR and T directly enter the inhalation dose
522 calculation through the exposure assessment equations provided in the Methods and
523 Supplementary Material (Eqs. 9 and 10). Consequently, reducing IR or adjusting T,
524 for instance, through improved ventilation or reduced working hours, can be an
525 effective strategy to increase the EL benchmark to an acceptable exposure

concentration (Buonanno et al., 2020; Guo et al., 2014). Although specific ventilation standards for WWTP dewatering facilities are limited, general occupational hygiene guidelines recommend adequate air exchange to dilute airborne contaminants, supporting ventilation as a practical risk mitigation measure in such settings (Frankel et al., 2012; Guo et al., 2014).

Existing occupational guidance for microbial hazards, such as OSHA recommendations for Legionella control in water systems, provides vital qualitative benchmarks for managing workplace health risks (Leiblein, 2020). However, these guidelines are primarily focused on waterborne exposure and outbreak prevention rather than quantitative airborne exposure limits (Olatunji et al., 2024). In contrast, the reverse-QMRA framework applied in this study enables the derivation of pathogen-specific, health-based exposure benchmarks for bioaerosols under defined occupational scenarios, thereby complementing existing occupational guidance (Engels, 2021).

4 Conclusion

This study demonstrates, for the first time in a municipal dewatering facility, that *E. coli* bioaerosol concentrations are strongly influenced by ventilation conditions, working postures, and seasonal variations. Poor ventilation consistently increased airborne concentrations, while stooping postures elevated exposure relative to standing, emphasizing the combined effect of environmental and behavioral factors on occupational risk. A major finding is the dominance of respirable fractions, which comprised 78–100% of total particles, primarily in the 1.1–2.1 μm range, with higher

proportions in summer, revealing previously unquantified seasonal exposure patterns. The derivation of ceiling-type EL benchmarks across different exposure scenarios further contributes to occupational hygiene knowledge, showing that PPE use substantially reduces effective exposure and raises safe EL thresholds. These results provide a quantitative basis for risk-informed mitigation strategies, particularly highlighting the importance of ventilation optimization and PPE. Future research should focus on the efficacy of engineered ventilation, standardization of bioaerosol ELs for industrial environments, and alternative mitigation strategies beyond PPE. Such work would build on the current findings to advance evidence-based occupational health standards and improve protection against airborne pathogens in industrial settings.

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Figures

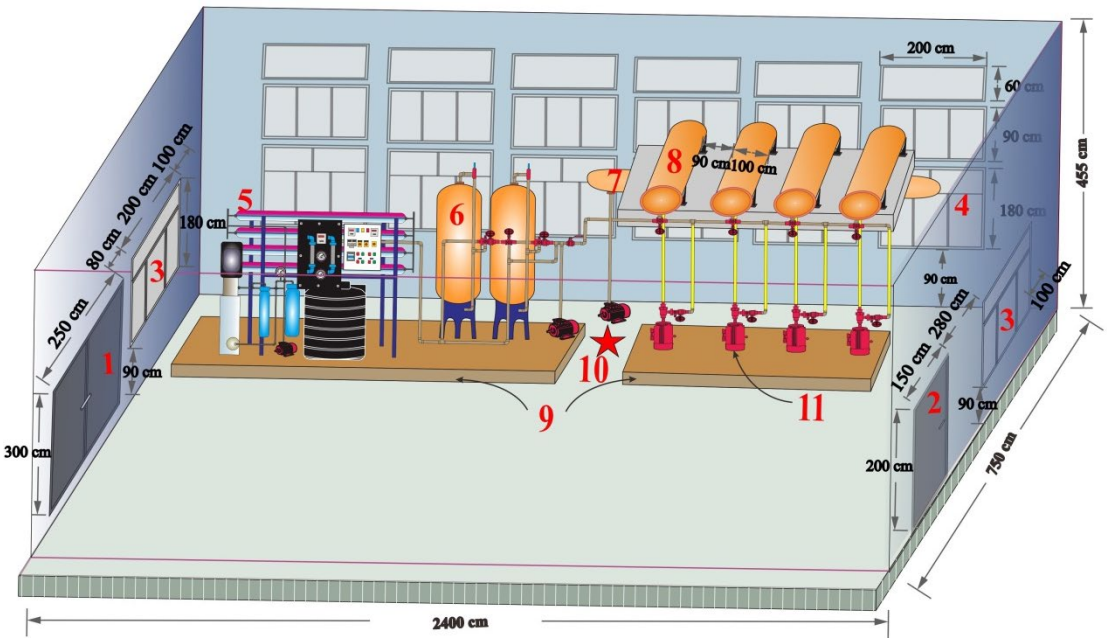


Fig. 1 Layout of the sludge dewatering facility and sampling point (1=front door; 2=back door; 3=small window; 4=big window; 5=dilution unit; 6=mixing tank; 7=screw conveyor; 8=horizontal screw decanter centrifuge; 9=pedestal; 10 (the star) =sampling point; 11=motor).

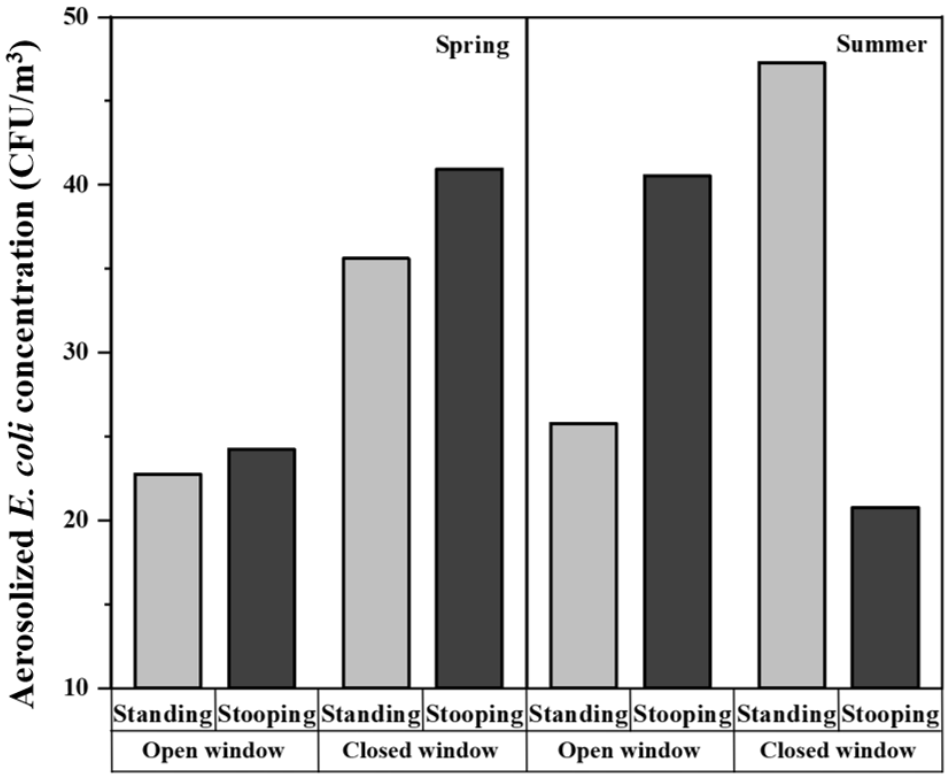


Fig. 2 Exposure levels of aerosolized *E. coli* concentrations to workers considering their working postures and seasonal conditions**.**

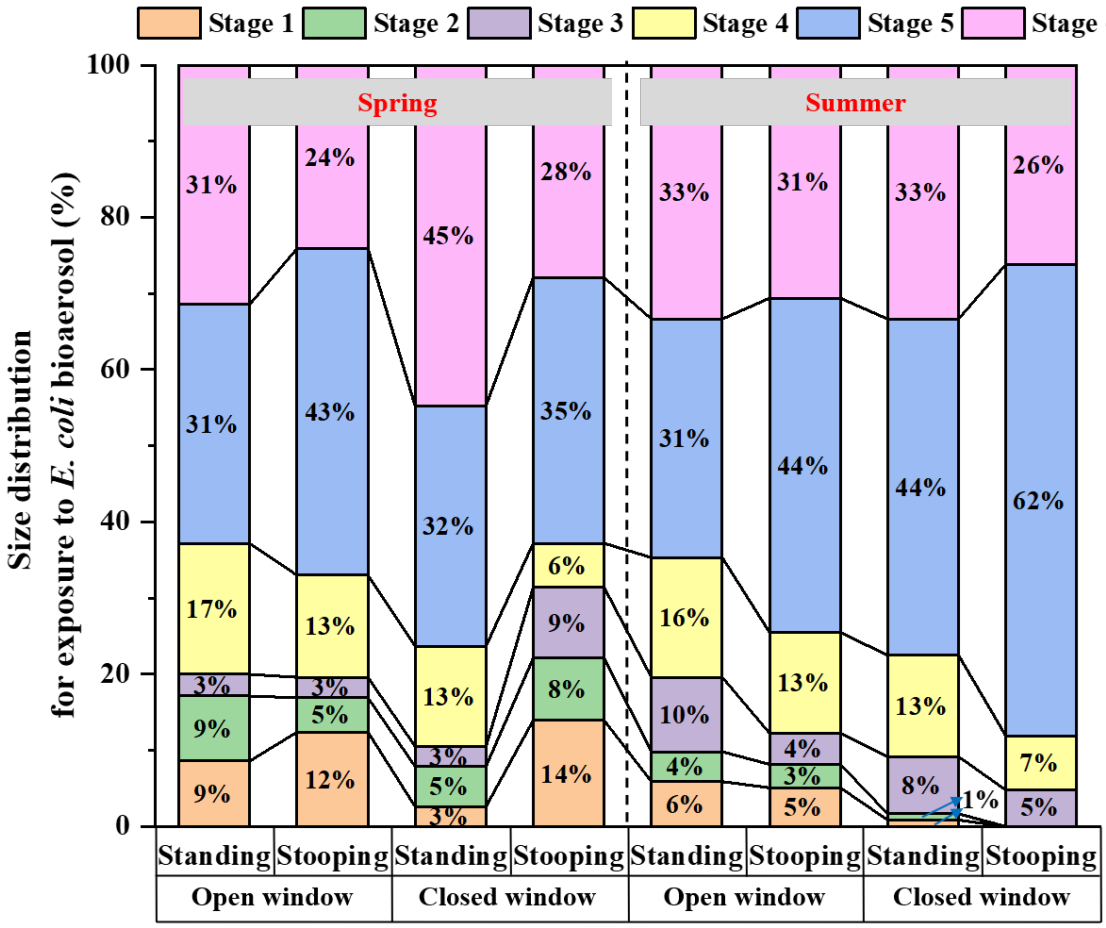


Fig. 3 Size distribution of *E. coli* bioaerosol particles

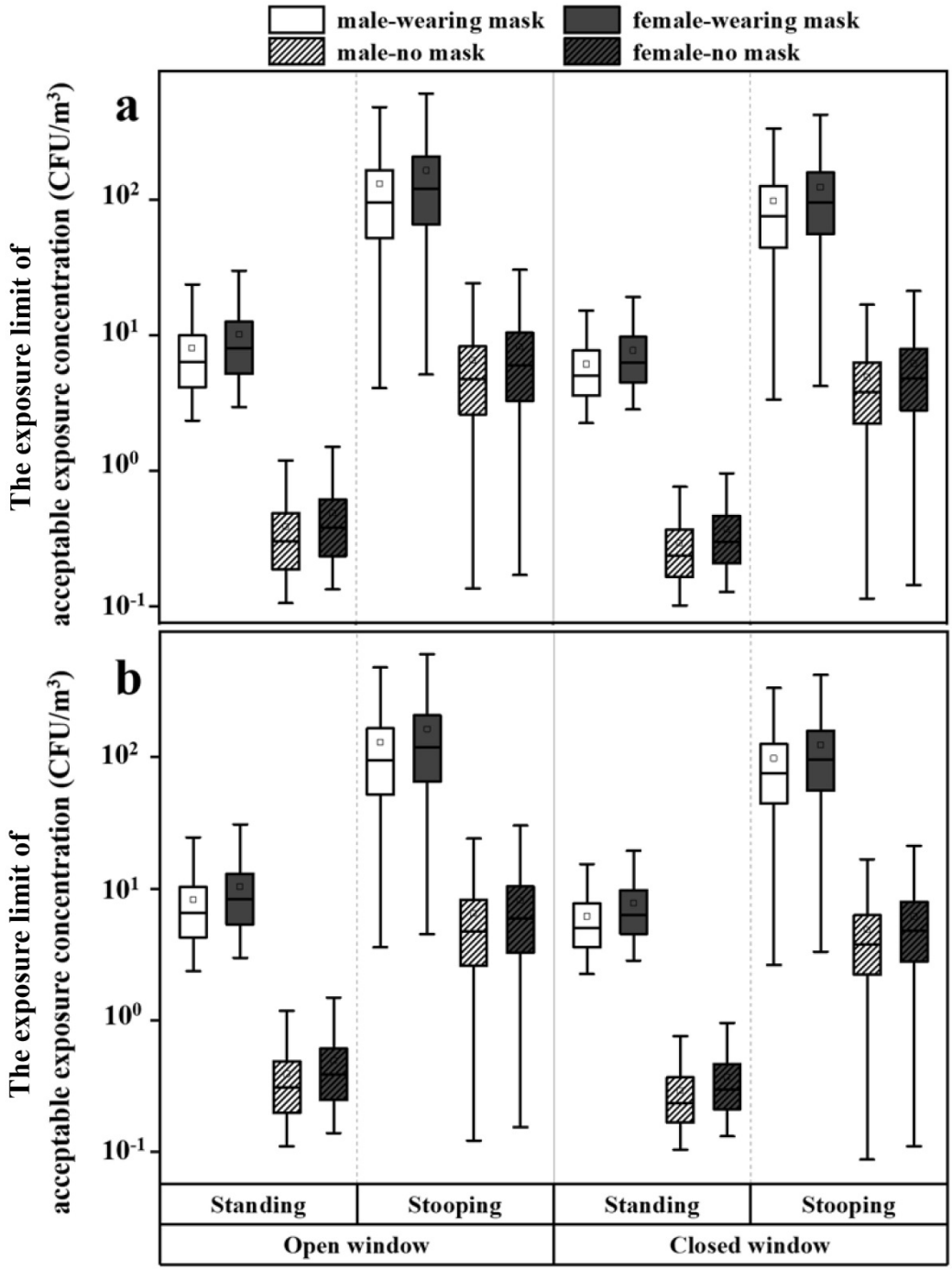


Fig. 4 Exposure limit of acceptable exposure concentration (CFU/m^3) for exposure to *E. coli* bioaerosol under stooping and standing working postures in (a) spring and (b) summer periods based on the health risk level of the U.S. EPA annual infection risk.

The bottom and top of the box respectively represent first and third quartiles (25th and 75th quantile value), the band inside the box represents the second quartile (median value), and the square inside the box represents the mean value. The bottom and top of the whiskers represent 2.5th (conservative estimate in worst-case condition) and 97.5th (optimistic estimate in best-case condition) percentile values, respectively.

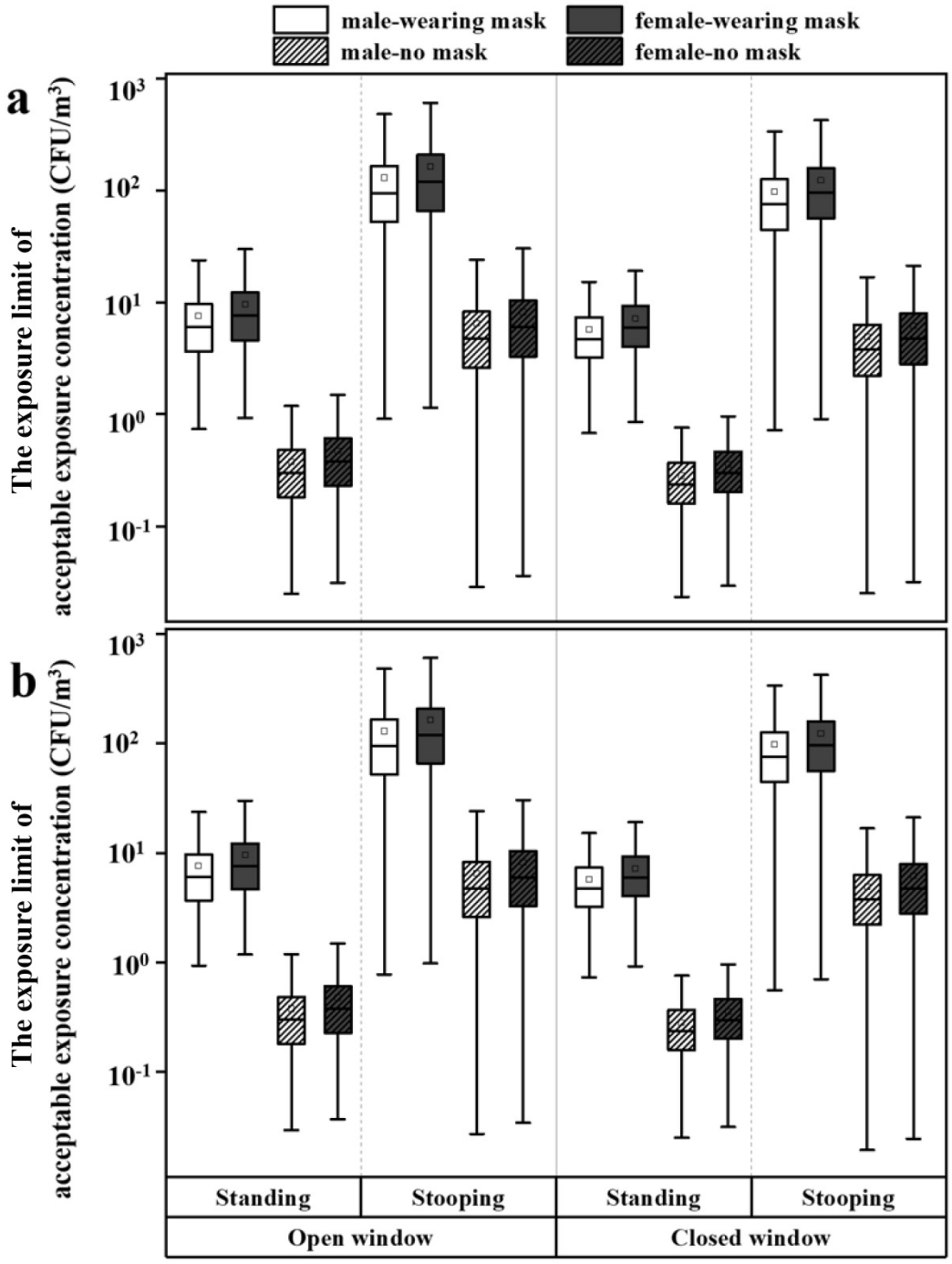


Fig. 5 exposure limit of acceptable exposure concentration (CFU/m^3) for exposure to *E. coli* bioaerosol under stooping and standing working postures in (a) spring and (b) summer periods based on the health risk level of the WHO disease burden.

The bottom and top of the box respectively represent first and third quartiles (25th and 75th quantile value), the band inside the box represents the second quartile (median value), and the square inside the box represents the mean value. The bottom and top of the whiskers represent 2.5th (conservative estimate in worst-case condition) and 97.5th (optimistic estimate in best-case condition) percentile values, respectively.

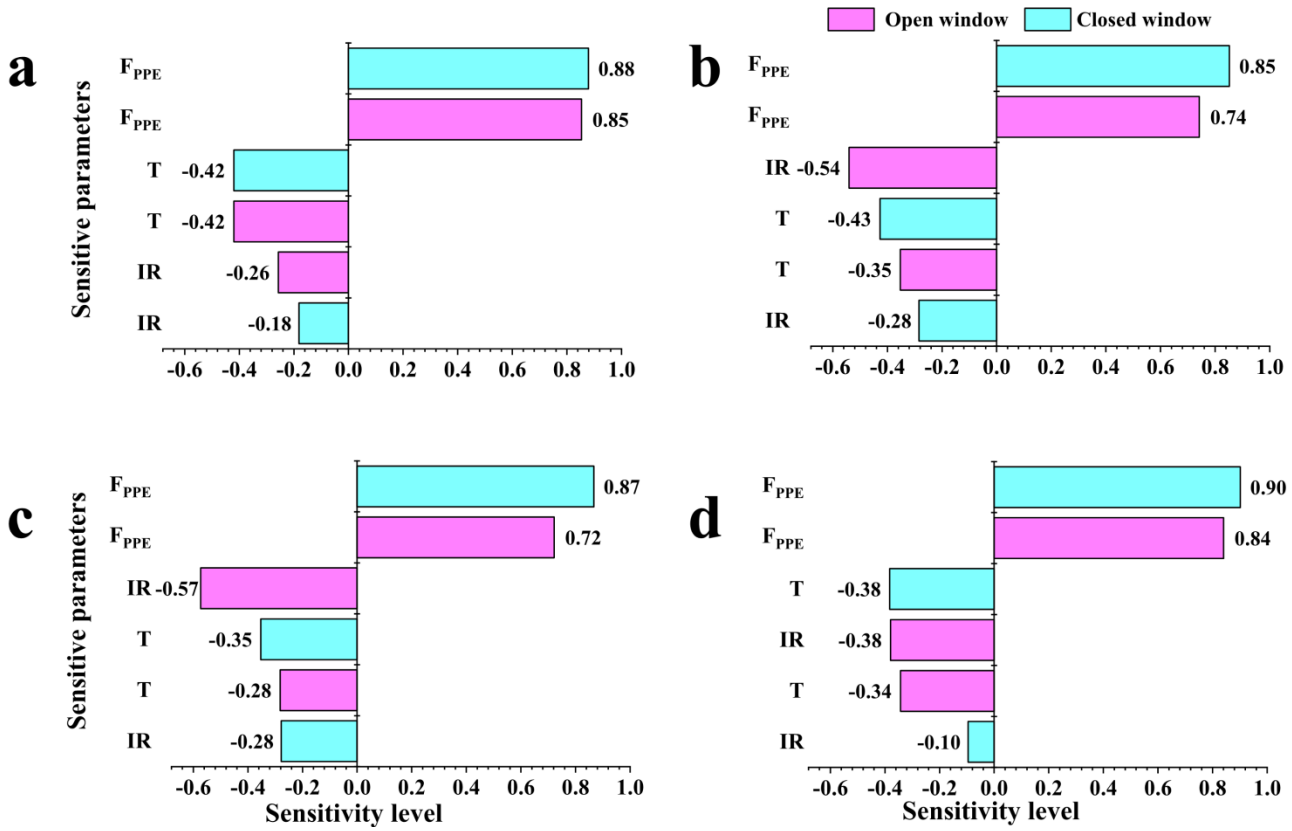


Fig. 6 Sensitivity level ranking of input variable parameters that affect the output values of exposure limit for exposure to *E. coli* bioaerosol under (a) standing and (b) stooping working postures in spring period; (c) standing and (d) stooping working posture in summer period. Correlation coefficient values were obtained using Oracle Crystal Ball sensitivity analyses and shown next to each bar.

F_{PPE}=removal fraction by equipping personal protective equipment.

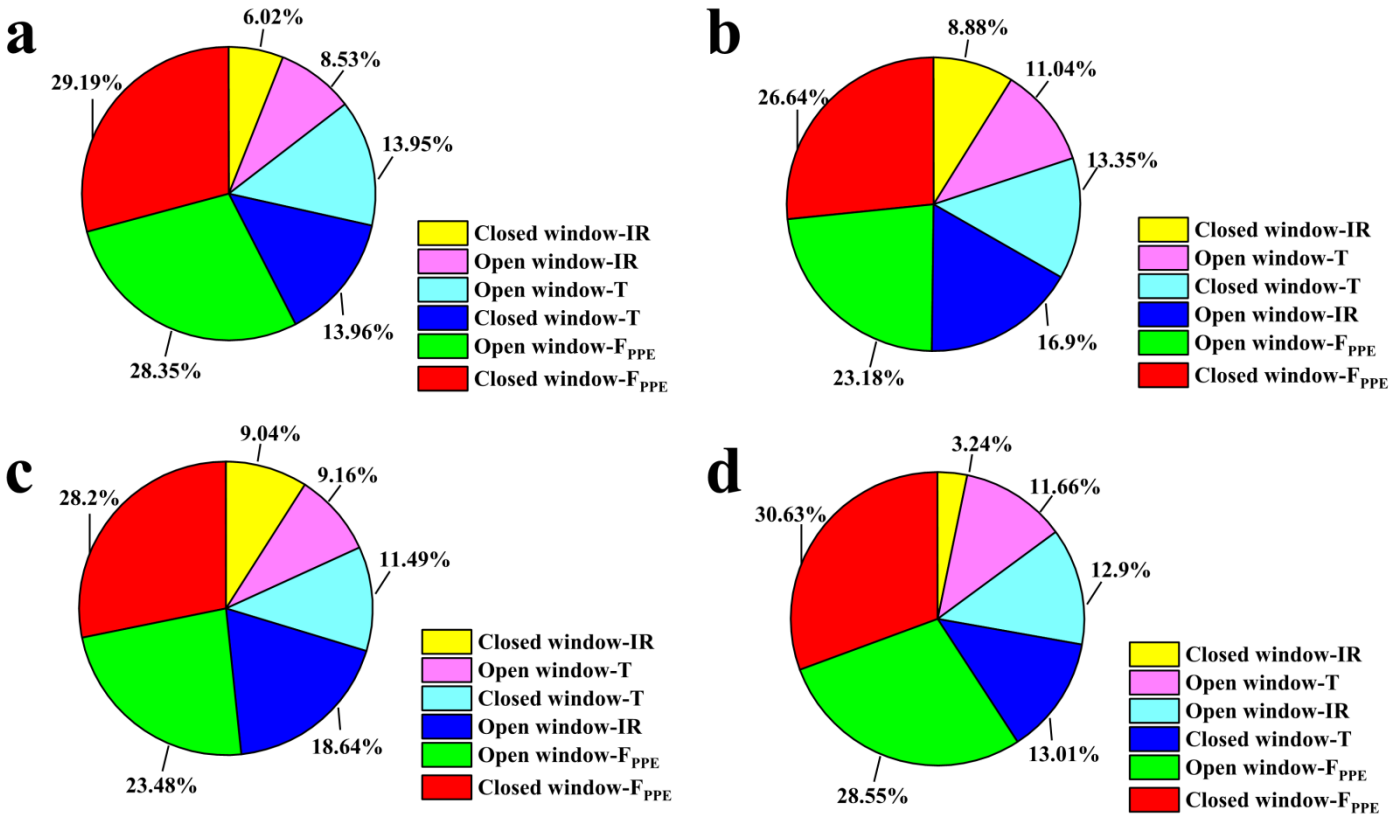


Fig. 7 Specific contribution of input variable parameters that affect the output values of exposure limit for exposure to E. coli bioaerosol under (a) standing and (b) stooping working postures in spring period; (c) standing and (d) stooping working posture in summer.
Contribution to variance values were obtained from the Oracle Crystal Ball sensitivity analyses and shown next to each pie. FPPE=removal fraction by equipping personal protective equipment.

Table 1 Descriptions of exposure issues

Items	Workers
Exposure events	Working in sludge dewatering house, excluding national statutory and public holidays
Exposure time in an exposure (working) day	Task-based time spent near operating centrifuges under specific working postures Uniform distribution (Min = 0.5 h; Max = 1 h) Average value = 0.75 h
Exposure frequency per year	n = 251 day*

* n = working days in a year, excluding national statutory and public holidays (114 days) in a year.

Table 2 Parameters for reverse quantitative microbial risk assessment calculation

Items	Description		Unit	Values	Reference
HB	Health burden		DALYs/ case	0.0455	Shi et al. (2018)
$P_{ill/inf}$	Specific conditional probability of illness given an infection		Unitless	1	Busgang et al. (2018)
n	Exposure frequency per year		d	Table 1	-
α	Beta-Poisson dose-response model parameter		Unitless	1.55×10^{-1}	Shi et al. (2018)
D_{50}				2.11×10^{6}	
Br	Breathing rate		L/min	Male: 18.65; female: 14.80	Duan (2013), Haas (2015)
T	Exposure time in an exposure (working) day		h	Table 1	-
*IR**	Bioaerosol respirable ratio in spring period	Open window; Standing working posture	Unitless	Uniform distribution (Min =0.63; Max = 1.00) Average value = 0.82	-
		Open window; Stooping working posture		Uniform distribution (Min = 0.33; Max = 1.00) Average value = 0.67	
		Closed window; Standing working posture		Uniform distribution (Min = 0.75; Max = 1.00) Average value = 0.88	
		Closed window; Stooping working posture		Uniform distribution (Min = 0.64; Max = 1.00) Average value = 0.82	
	Bioaerosol respirable ratio in summer period	Open window; Standing working posture		Uniform distribution (Min = 0.25; Max = 1.00) Average value = 0.63	
		Open window; Stooping working posture		Uniform distribution (Min = 0.50; Max = 1.00) Average value = 0.75	
		Closed window; Standing working posture		Uniform distribution (Min = 0.60; Max = 1.00) Average value = 0.80	
		Closed window; Stooping working posture		Uniform distribution (Min = 1.00; Max = 1.00) Average value = 1.00	
F_{PPE}**	Removal fraction by equipping personal protective equipment		Unitless	Uniform distribution (Min = 0.95; Max = 0.99)	Haas et al. (2017)

*The aerosol respirable ratio (*IR*) is the ratio of bioaerosol concentration from the 3-6 to 1-6 of the Andersen six-stage cascade impactor. Its minimum value was set at the minimum ratio of bioaerosol concentrations calculated from the data collected during the field sampling campaign (Supplement Material Table 4). The maximum value of *IR* was set to 1 in accordance with the work of Shi et al. (2018). **For the removal fraction by equipping personal protective equipment (F_{PPE}): this study assumed that the personal protective equipment was a series of mask at which the level of filter efficiency was between N-95 and N-99. According to the Occupational Safety and Health particulate filter tests, the 95% and 99% levels of filter efficiency of N-95 and N-99 masks were certified, respectively. Therefore, for convenience of reverse-QMRA calculation, F_{PPE} had minimum and maximum values of 0.95 and 0.99, respectively (Hass et al., 2017).



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Worker exposure to bioaerosols from sludge dewatering facilities: risks and mitigations

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