

Measurement of ventilation effectiveness and indoor air quality in toilets at mass gathering events

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ABSTRACT

Mass gathering events were closed in 2020 to reduce the spread of SARS-CoV-2. These events included music concerts, theatre shows, and sports matches. It is known, however, that the long-range aerosol transmission of pathogens, such as SARS-CoV-2, can be reduced with sufficient ventilation indoors. This paper examines the risk of reopening these mass gathering events by measuring the CO₂ concentration, as a proxy for ventilation effectiveness, at 58 events, with a specific focus on small enclosed spaces with short occupancy. Toilets (sanitary accommodation) are spaces that are densely and continuously occupied for short durations throughout the events, such as during theatre intervals or half-time at sports events. The results showed that the average air quality in toilets was good at most events. There were, however, considerable peaks in CO₂ concentration of up to 3431 ppm in toilets at times when occupancy was presumed high, indicating that the risk of exposure to exhaled breath, which may contain virus-laden aerosols, is higher in toilets than elsewhere in the venue (although occupancy duration will be much lower). Recommendations are provided to encourage building designers and operators to be mindful of the ventilation strategies used in toilets given their occupancy and size.

KEYWORDS

Indoor air quality; ventilation effectiveness; mass gathering events; CO₂ monitoring; post-occupancy evaluation.

1 INTRODUCTION

Confined spaces with transient occupancies, such as toilets (sanitary accommodation¹), have been identified as potentially high-risk areas for the transmission of airborne pathogens (Dancer et al., 2021; Malki-Epshtein et al., 2023). At mass gathering events, these enclosed spaces can be crowded with many people mixing in proximity for brief periods, such as during half-time at sports matches or during intervals at theatres (Adzic et al., 2022). This increases the risk of both short-range and long-range airborne transmission. Person-to-person transmission of pathogens is compounded in toilets by faecal particles entering the air by flushing toilets (Best et al., 2012; Cai et al., 2022; Knowlton et al., 2018). A possible faecal-

¹ Sanitary accommodation is a space containing one or more flush toilets or urinals (HMG, 2021a) and are hereafter referred to as “toilets”.

oral SARS-CoV-2 transmission route has been identified (Guo et al., 2021) leading to toilets being considered a contact hub for community transmission of SARS-CoV-2 (Dancer et al., 2021).

Ventilation which introduces uncontaminated air into a space is an important mechanism to reduce long-range transmission of airborne pathogens, but in transiently occupied spaces the ventilation rates may not be adequate to introduce enough uncontaminated air during the brief period of dense occupancy to dilute or remove airborne pathogens (Dancer et al., 2021). In England, building regulations require sanitary accommodation to be ventilated at 6 l/s per toilet pan or urinal via extract ventilation to minimise the spread of water vapour and pollutants to other parts of the building (HMG, 2021a). The aim of the work reported in this paper was to measure the ventilation effectiveness of outdoor air in toilets at mass gathering events. The aim was achieved by measuring the carbon dioxide (CO₂) concentration in the air of 11 toilets at three venues hosting 58 mass gathering events which were run as part of the UK Government Events Research Programme in 2021 (DCMS, 2021; HMG, 2021b). CO₂ concentration is used as a proxy for exhaled breath and allows for the rapid assessment of indoor air quality (Malki-Epshtein et al., 2023).

2 METHOD

The concentration of CO₂ in the indoor air was measured in 11 toilets in three different venues at 58 live mass gathering events (Table 1). Toilets are of interest because they are usually spatially constricted areas that are densely occupied for brief periods during mass gathering events with potentially insufficient ventilation relative to the occupancy levels. The three venues (Table 1) hosted between 79 and 90,000 people at a variety of events. The snooker and football matches at the Crucible Theatre and Wembley Stadium were sporting events in which the games were played in two halves. This meant that there were three periods where toilets were densely occupied: (1) pre-event, (2) mid-event interval, and (3) post-event, although attendees were able to occupy the toilet at any time during the event. The music awards ceremony (BRIT Awards) at the O2 Arena was televised with frequent advertisement/commercial breaks of up to 15 minutes when presenters and performers would not be on stage. It was at these times that people were most likely to leave the auditorium to occupy the toilets, although they were able to visit the toilets at any time. The toilets were mechanically ventilated in all venues. This non-interventionist, observational monitoring study took place during a series of Events Research Programme pilot events which examined the risk of reopening due to long-range airborne infections after COVID-19 pandemic closures (DCMS, 2021; HMG, 2021b).

Table 1: Names and details of venues monitored.

Event	Venue	No. events	Date (DD/MM/2021)	No. toilets	No. attendees (range)	% capacity
World Snooker Championships	Crucible Theatre	46	17/04 to 03/05	6	79-862	8-88
Music awards	O2 Arena	1	11/05	3	3532	18
Football matches	Wembley Stadium	11	18/04 to 11/07	2	2700-90000	3-100

CO₂ concentration was measured at 2-minute intervals using non-dispersive infrared sensors (400-5000 ppm; ± 30 ppm) that were calibrated prior to use and routinely auto-calibrated during operation (Malki-Epshtein et al., 2023). The sensors were placed on walls at a height of 1.6 to 2.3 m above the floor, and away from vents, doors, or windows. The number of sensors installed in each space varied according to the room geometry and volume, but typically there were 1-2 sensors in each toilet.

CO₂ concentrations are of interest because elevations above typical ambient levels (420-500ppm) indicate exposure to exhaled breath, in the absence of other sources. The higher the concentration of CO₂ above typical ambient levels, the higher proportion of indoor air that has been exhaled by the occupants of the space. Ventilation is the primary removal mechanism of CO₂ in most spaces via dilution with outdoor air. Measurement of CO₂ concentration, therefore, indicates the amount of ventilation of outdoor air being received in a space relative to the occupancy levels.

Air quality classifications were used to classify each toilet by the measured mean average and maximum CO₂ concentration during each event (Table 2). Average CO₂ concentration was both the temporal and spatial average, whereas maximum CO₂ was the single point in time with the highest CO₂ concentration measured at one particular sensor location in the space. Each space was assigned a band, from Band A (high ventilation relative to the occupancy) to Band G (low ventilation relative to the occupancy). The bands were devised during the UK Government Events Research Programme to rapidly assess indoor air quality at mass gathering events (Malki-Epshtein et al., 2023). CO₂ concentration alone does not indicate a risk of transmission of airborne pathogens (Iddon et al., 2022; Jones et al., 2021) but it does allow for the rapid assessment of ventilation effectiveness relative to the occupancy levels.

Table 2: Air quality classifications and bands.

Air quality classification	Band	Range of absolute CO ₂ concentrations (ppm)
At or marginally above outdoor concentration.	A	400-600
Target for enhanced aerosol generation (e.g., singing or aerobic activity).	B	600-800
Typical air quality design standards for offices.	C	800-1000
Medium air quality.	D	1000-1200
Design standard upper limits for most schools pre-COVID-19.	E	1200-1500
Priority for improvement.	F	1500-2000
Low ventilation and/or dense occupancy. Must be prioritised for improvement.	G	>2000

3 RESULTS

3.1 Air quality classifications for all mass gathering events monitored

Analysing the spatiotemporal average CO₂ concentration showed that the majority of toilets (96%) were in air quality Band A and Band B with the remainder (4%) in Band C and Band D (Figure 1). For maximum CO₂ concentrations, however, air quality bands in toilets were in Band A and Band B for fewer events (76%) and whilst some toilets in some events were classified as Band E, Band F, and Band G, they were relatively small in number (5% of events) (Figure 1). This indicates that ventilation was generally sufficient given the occupancy levels in most toilets.

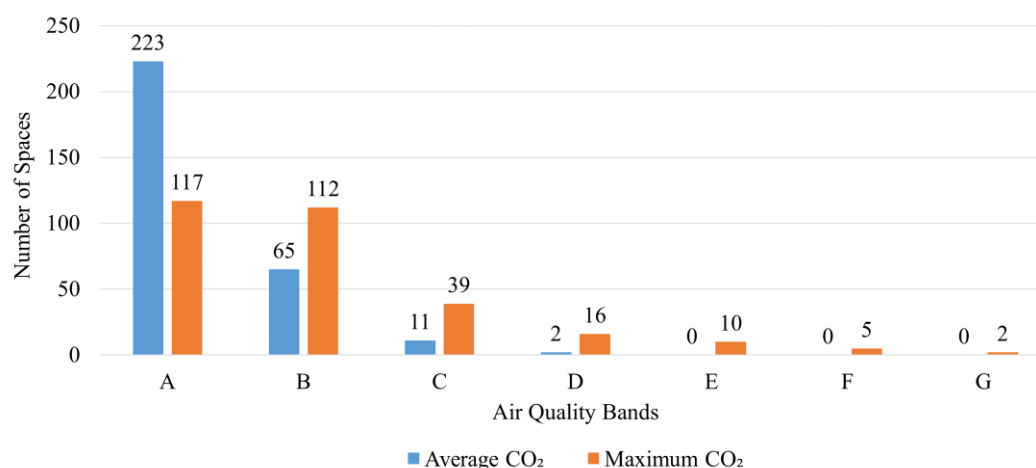


Figure 1: Air quality classification bands for toilets.

3.2 CO₂ concentration time series profiles at different events

A higher proportion of toilets are in air quality Band E, Band F, and Band G when classifying using maximum CO₂ concentration than when using average CO₂ concentration. This indicates that there are peaks in CO₂ concentration at specific times that are not sustained throughout the event. This is evidenced by investigating plots of CO₂ concentration against time (Figures 2-4).

Crucible Theatre (snooker matches)

At the Crucible Theatre, three distinct peaks in CO₂ concentration were observed which corresponded to the event starting, during the interval, and at the end of the event (Figure 2²). At other times, the CO₂ concentrations reduced to reach a quasi-steady state as most of the spectators were inside the theatre auditorium during the event.

Higher maximum and baseline CO₂ concentrations were observed in three toilets in the Crucible Theatre (unisex toilet AS7, male AS8, and unisex AS9) compared to the other toilets in the same venue (Figure 2). These three toilets were located close to the main theatre auditorium entrance, whereas the others were on floors either below or above the main entrance. Event observers confirmed that the toilets by the main entrance (AS7, AS8, and AS9) were the most visited even though event managers communicated that there were alternative toilets available on other floors. Event average CO₂ concentrations in all toilets close to the main auditorium entrance (first floor) were at least 32% higher than average CO₂ concentrations in toilets on the ground and second floor. Male toilet AS8 showed particularly high CO₂ concentrations relative to the other toilets, reaching a maximum concentration of 1600 ppm and being 400 ppm higher than the next highest concentration (Figure 2).

It was also observed that the CO₂ concentrations in toilets AS7, AS8, and AS9 did not fall below 600 ppm, even during periods assumed to be unoccupied. This is because extractor fans drew makeup air through toilet door grilles from densely occupied adjacent spaces in which maximum CO₂ concentrations of 1303 ppm were recorded.

² The example of 3 May 2021 is provided as this is the event with the highest occupancy (88% of usual capacity), but the trimodal pattern was generally observed at all events at the Crucible Theatre.

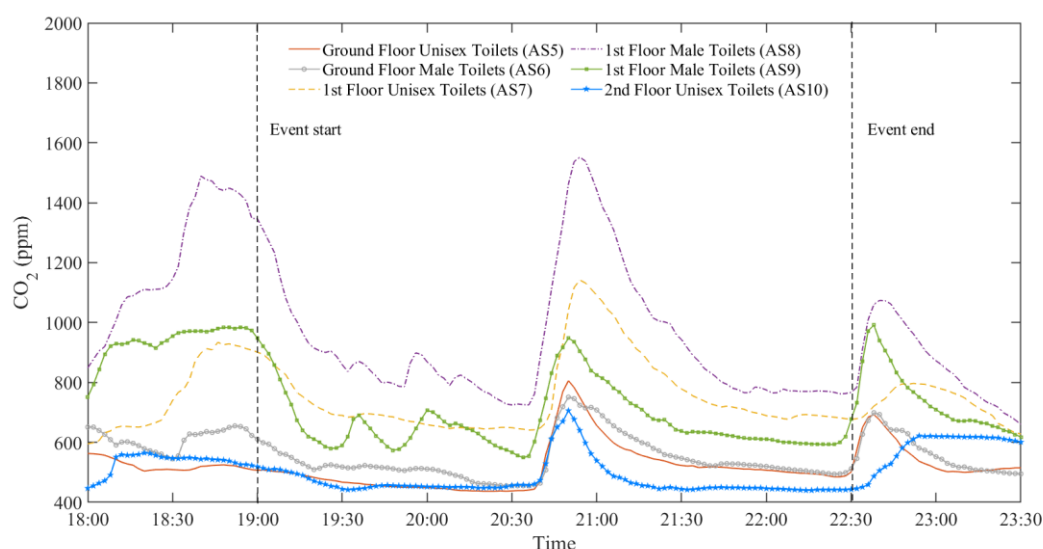


Figure 2: Measured CO₂ concentration time series profile in six toilets in the Crucible Theatre at the World Snooker Championships on 3 May 2021.

Wembley Stadium (football matches)

At Wembley, CO₂ concentration time series profiles were observed that were similar to those recorded at the Crucible Theatre with trimodal peaks before an event, at half time, and at the end of the event (Figure 3). These peaks were most pronounced at the high occupancy events but were observed even when the occupancy levels were significantly lower than usual (at 3% of usual capacity in a male toilet, Figure 3b; and 3% in a female toilet, Figure 3a). There were higher maximum CO₂ concentrations recorded during the events with higher occupancy levels. In the female toilet, the maximum CO₂ concentration was 68% higher at the 100% occupancy event compared to the 65% occupancy event (Figure 3c) and 154% higher in the male toilet comparing the 20% and 100% occupancy events (cf. Figure 3b and Figure 3d). Generally higher CO₂ concentrations were observed in the male toilet compared to the female toilet on the same floor level at the same football match due to a greater proportion of males at these events. During the 100% occupancy events, the maximum recorded CO₂ concentration was 3431 ppm in the male toilet versus 1320 ppm in the female toilet (i.e., 160% higher in the male toilet). The CO₂ concentration remained continuously elevated above 1500 ppm (classed as a priority for improvement, Table 2) for periods in male toilets at all the football matches where the occupancy was greater than 65% (Table 3).

Table 3: Comparing the occupancy to the longest continuous number of minutes where CO₂ concentration was above 1500 ppm.

Occupancy as a percentage of usual capacity (%)	Minutes CO ₂ concentration >1500 ppm				
	Before event	First half	Half-time interval	Second half	After event
65	0	0	6	2	4
72	32	0	15	6	16
100	44	0	15	4	8

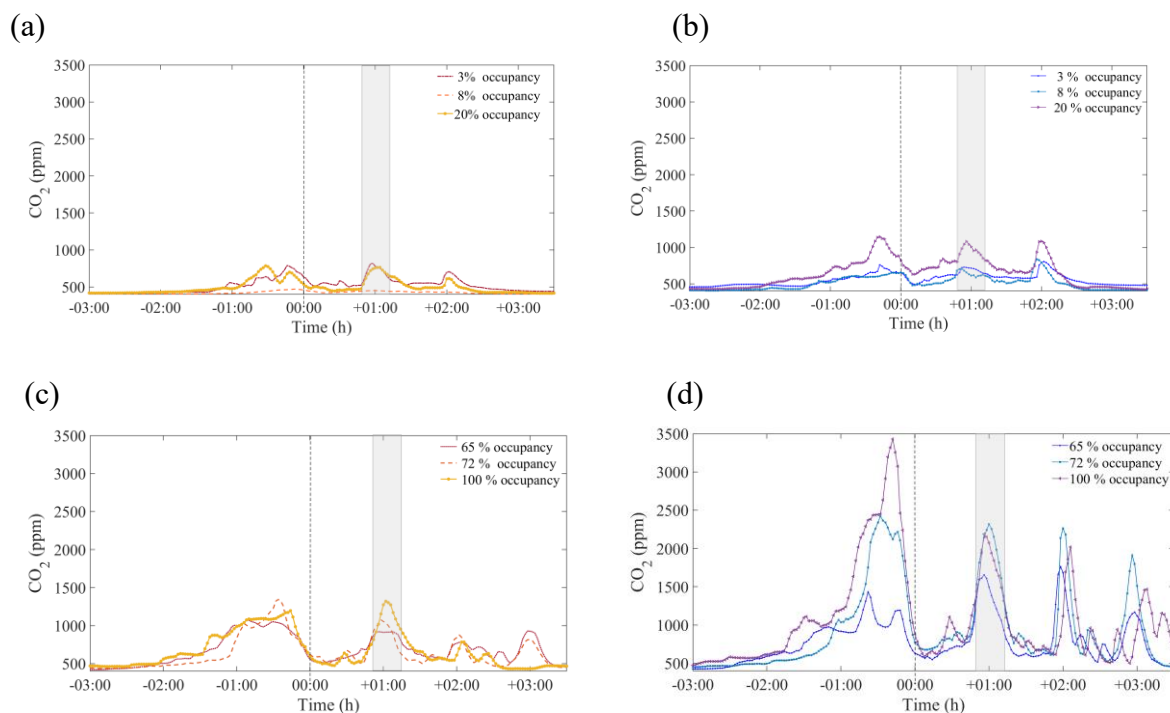


Figure 3: Measured CO₂ concentration time series profile in six toilets during football matches at Wembley Stadium with varying occupancy levels: (a) being a low occupancy event (3 to 20%) in a female toilet; (b) low occupancy event (3 to 20%) male toilet; (c) high occupancy event (65 to 100%) female toilet; (d) high occupancy event (65 to 100%) male toilet. The dashed vertical line indicates the football match kick-off time, and the shaded region is the half-time period.

O2 Arena (music awards ceremony)

Unlike the sports events held at the Crucible Theatre and Wembley Stadium, the music awards ceremony at the O2 Arena did not have a specific half-time interval, but instead a series of 15-minute advert/commercial breaks because the show was televised. Toilet visits were more evenly spaced and this is reflected in the flatter CO₂ concentration profile, which does not feature pronounced peaks during the event (Figure 4). Despite the significantly reduced occupancy (18% of usual capacity), the female toilet on Level 1 reached a maximum CO₂ concentration of 1169 ppm and was sustained above 1000 ppm for over two hours (Figure 4). The male toilets, located just next to the female toilets on Level 1, presented with a peak CO₂ concentration of 1100 ppm just prior to the event starting but then fell to an average below 750 ppm during the event. Nonetheless, the CO₂ concentrations recorded inside the toilets were considerably higher than those immediately outside the toilet (see queuing area, Figure 4).

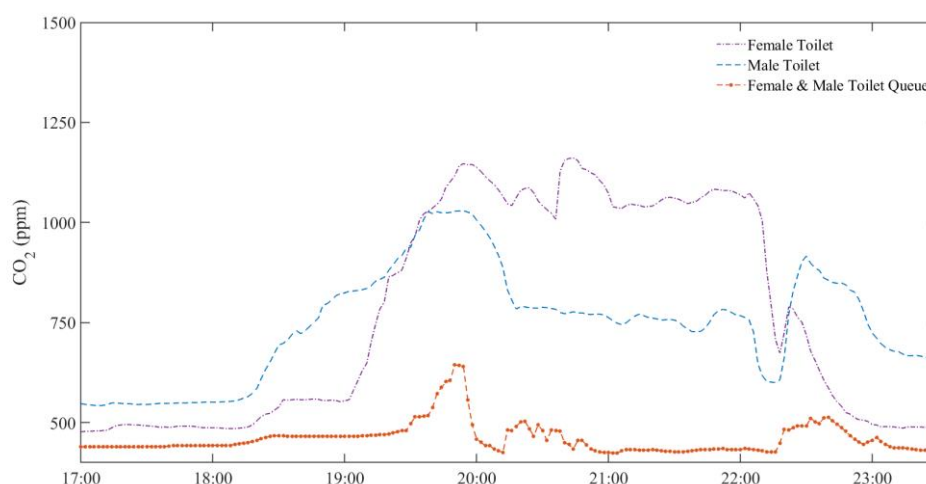


Figure 4: Measured CO₂ concentration time series on Level 1 at the O2 Arena during the music awards event at 18% of usual occupancy capacity.

3.3 Effect of occupancy levels

It has been demonstrated that higher occupancy levels drive an increase in CO₂ concentration (Figure 3 and Figure 4), as this is the only significant factor believed to change between events (the ventilation systems were otherwise operated identically). At the Crucible Theatre, where CO₂ concentration was monitored in toilets during 46 events from 8 to 88% of the venue's usual occupancy capacity, the effect of occupancy on maximum CO₂ concentration is apparent in all toilets, but especially the frequently visited toilets (those which are easily accessible due to proximity to the auditorium entrance: AS7, AS8, AS9) (Figure 5). At low occupancy events, e.g., around 10%, all maximum CO₂ concentrations were below 800 ppm, but the trend line indicates maximum CO₂ concentrations of over 2000 ppm might be expected in some toilets (AS8) at fully occupied events (Figure 5).

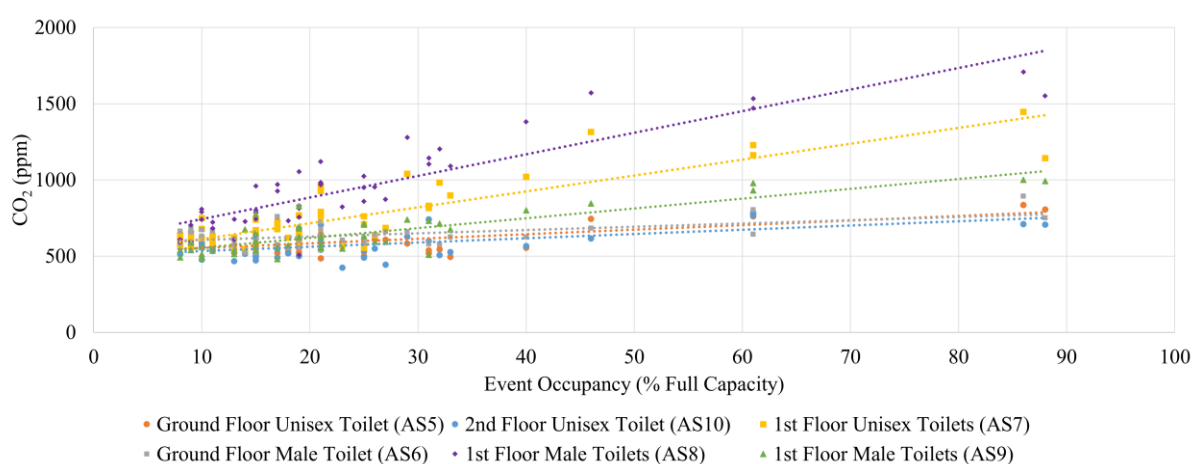


Figure 5: Event occupancy versus maximum CO₂ concentration in toilets at the Crucible Theatre.

4 DISCUSSION

The measurement of CO₂ concentration in indoor air does not indicate the risk of long-range transmission of airborne pathogens, but it is a useful way of rapidly assessing the level of ventilation relative to the occupancy of a particular space. Most of the toilets were deemed to be sufficiently ventilated, but a small number were targeted for improvement using the maximum CO₂ concentration as a performance metric. The proximity of the toilet to important areas in each venue, such as the main auditorium door in the Crucible Theatre, was also an important indicator of performance, with toilets proximate to these places more frequently occupied and so recording higher CO₂ concentrations. This perhaps suggests the ventilation systems are undersized to cope with the short periods of very high occupancy.

For structured events with a seated audience, it has previously been recommended that intervals are a useful means to reduce the CO₂ concentration in the main event space (e.g., a theatre auditorium) because it provides a period of reduced occupancy during which the space can be ventilated whilst the occupant emission rates are lower before the space becomes occupied again (Adzic et al., 2022). For toilets, however, these intervals cause brief periods of high occupancy with maximum CO₂ concentrations reaching 2250 ppm during half-time at a Wembley Stadium football match. This is compared to much lower, consistent CO₂ concentrations at the O2 Arena where toilets were visited throughout the event rather than just during the intervals. Whilst it would not be possible to introduce additional breaks in play in structured sports games, there may be other types of events where this is possible or, equally, the interval could be for a longer time to reduce the crowding that occurs in toilets with short interval durations.

Most Events Research Programme pilot events were run at reduced capacity compared to normal operations, but Wembley Stadium hosted one full-capacity event (Table 1). The measured CO₂ concentrations are influenced by both the ventilation provision and the number of occupants in the space. Reduced occupancy has a clear benefit in terms of maintaining lower CO₂ concentrations in spaces (Figure 5) but running events at such reduced capacities is not economically viable. Venue operators should instead consider ways to better disperse the event attendees around the various toilets in the venue to avoid overcrowding in any particular toilet. At the Crucible Theatre, for example, venue operators changed some toilets to unisex to reduce overcrowding in the male toilets. Alternatively, additional temporary toilets could have been installed, providing they are located close enough to the main event space to be used. Designers of new buildings to host mass gathering events could consider adding additional toilets to reduce occupant density and providing more in locations where crowds are likely to congregate, although this will result in higher construction, maintenance, and cleaning costs. Building designers should carefully consider toilet location to ensure all are used evenly or those in the densely occupied areas are larger or provided with a higher ventilation rate. Ventilation designers should also consider where makeup air is being drawn from, to avoid air being drawn from densely occupied neighbouring spaces, potentially containing virus-laden aerosols.

A limitation of this work is that not all events were run at full capacity. CO₂ concentrations are likely, therefore, to be higher when returning to full capacity than was measured in most of these examples. It did, however, provide a useful and rare opportunity to compare events with different occupancy levels in the same venue. An additional limitation is that only CO₂ concentration was considered and so the risk of long-range airborne transmission cannot be made without further analysis (Iddon et al., 2022; Jones et al., 2021). This analysis will be a

feature of future work, as will the assessment of microbiological data (air and surface samples) which were collected alongside the CO₂ measurements, but not presented here. The exposure time in toilets is likely to be low, as people do not tend to dwell there, so the risk of long-range transmission in toilets is likely to be low, irrespective of ventilation levels. However, there are other impacts of overcrowding that these data highlight, such as the scope for short-range airborne and fomite transmission in the relatively small toilet spaces. Neither of these factors were considered in this paper but will be addressed in future work. A key limitation of this work is that the exposure period of the occupants was unknown, but this has a great influence on the susceptibility of a person to infection from an airborne pathogen. Collecting data regarding this would be useful in future studies.

5 CONCLUSIONS

The mean average CO₂ concentration in 11 toilets was indicative of ventilation that was sufficient relative to the occupancy levels at 96% of the 58 events. Investigation of the maximum CO₂ concentrations, however, revealed that at some events there were intermittent periods of high CO₂, which indicated poor ventilation relative to the number of occupants. This mainly occurred during half-time intervals at the snooker and football matches, particularly during the higher occupancy events, and in toilets closest to auditorium entrances.

The key recommendations are summarised:

1. Increase the ventilation rates or the room volume in toilets which are expected to be most frequently visited (e.g., those close to auditorium entrances).
2. Increase the number of intervals, or their length in time, where possible, to spread out the occupancy of toilets over a longer period.
3. Increase the number of toilets available to reduce crowding and group them in places of high occupant density.
4. Change the admittance gender for some toilets if there is a predominantly male or female audience at a particular event.
5. Consider where supply air to toilets is being drawn from and avoid doing this from densely occupied adjacent spaces.

Future development of this work will consider translating the measured CO₂ concentration to an estimation of the risk of long-range airborne transmission of pathogens such as SARS-CoV-2 and will analyse the microbiological data measured at these events.

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