

Indoor Air Quality and Thermal Environment Across Three Leather Footwear Facilities in Agra India

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Abstract

Field evidence on indoor air quality and thermal environment from small-scale Indian manufacturing remains scarce, particularly for leather footwear. We monitored particulate matter, carbon dioxide (CO₂), formaldehyde, volatile organic compounds, temperature, humidity, and air velocity across three leather footwear facilities of differing scale and ventilation in Agra, India, over 27 months (608 sessions). Two-way ANOVA (facility by season) showed between-facility differences dominated variance for every parameter (partial eta-squared 0.10–0.87); mean PM_{2.5}, CO₂, formaldehyde and volatile organics were 2.0-, 1.9-, 3.0- and 3.5-fold higher in the cottage than organized facility. Season dominated particulate matter and thermal variables but not gas-phase pollutants, tracking ventilation rather than climate. Indoor/outdoor PM_{2.5} ratios rose from 0.48 to 1.00 across facilities, and CO₂ exceeded the ASHRAE ventilation threshold in 99.5% of cottage sessions versus 0% in the organized facility. As one facility represents each tier, these associations are hypothesis-generating, not evidence of a general scale effect.

Introduction

Indoor air quality (IAQ) has been studied as a distinct environmental health discipline for over three decades [1–3]. Indoor environments account for the large majority of human time-exposure, and the combined quality of indoor air and the thermal environment is recognised as a determinant of health, comfort, and productivity comparable in importance to outdoor air pollution [4–5]. Household and ambient air pollution together were estimated to account for over a million deaths annually in India alone [5], and the COVID-19 pandemic sharpened regulatory attention on ventilation and indoor air quality in the built environments where people work [6–7]. Indoor air quality and thermal comfort are increasingly studied as a coupled system rather than as independent domains, because ventilation strategy simultaneously governs pollutant dilution and the thermal energy balance of a space [8–10].

A substantial field-based literature documents this IAQ-thermal interaction across building typologies, including naturally ventilated and air-conditioned classrooms [11–12], offices [13–14], and residential dwellings [15–16]. Heavy-industry IAQ assessment remains comparatively rare, with refinery-sector monitoring one of the few available industrial precedents [17]. In India specifically, adaptive thermal comfort envelopes have been developed through a body of adaptive thermal comfort research that was built upon the India Model for Adaptive Comfort field study [18] and further developed through office [19], gender [20] and naturally ventilated buildings [21, 22] studies. However, this literature tends to be based in institutional, residential or office settings. There is no scale differentiated indoor air quality or thermal environment standard enforced to small-scale manufacturing workplaces in India in comparison to other developed regulatory frameworks [24]. The data on occupational fields on the small and micro-scale manufacturing sector is also limited, as this sector is where most of the informal sector in the country is employed.

This evidence gap is very visible in the leather footwear sector. It is of particular interest because it involves two occupational exposure pathways of proven health concern: solvent/adhesive vapour emission from pasting (sole-attaching) operations, which are usually conducted manually and the use of limited local exhaust, and particulate generation from cutting, buffing and lasting operations. Current literature on the sector has geographically disjointed and narrow topical focus: respiratory microplastic burden in shoe manufacturing workers in Spain [25]; oxidative stress associated with low-level VOC exposure in shoe industry workers from Serbia [26]; noise, temperature and light exposure in Bangladeshi shoe factories [27]; shoe-quality perception among shoe industry workers in the Philippines [28]; and occupational health risk among leather tannery workers in Kanpur, India [29]. None of these studies report simultaneous, standards-referenced field measurement of IAQ and thermal environment across facilities of differing scale within leather footwear manufacturing specifically, and none employs a factorial design capable of separating between-facility differences from season.

This distinction matters because India's leather footwear industry, like much of its manufacturing base, is stratified into organized (registered, larger, better-capitalised) units, micro/small/medium enterprises (MSMEs), and unregistered cottage or household-scale units, each operating under markedly different ventilation infrastructure, capital availability, and regulatory visibility [30–31]. General building-science evidence indicates that mechanical ventilation, filtration, and envelope control are primary determinants of indoor pollutant concentration and indoor/outdoor exchange [32–33], while a separate body of evidence emphasises outdoor infiltration and seasonal climate as a dominant driver of indoor particulate matter in residential and institutional settings [34–35]. Whether between-facility differences, for which ventilation infrastructure is a plausible but unconfirmed proxy, or season, a proxy for outdoor climate and infiltration, more strongly track occupational IAQ and thermal environment quality has not previously been examined within a single field design in an Indian manufacturing context.

Following recent calls for statistical transparency in human-centric building and IAQ research [36–37], we report a 27-month field monitoring campaign (December 2023–February 2026) across three leather footwear manufacturing units of different scale in Agra, Uttar Pradesh, a major Indian leather footwear cluster. Because this design compares a single facility per scale tier, it is a case study of these three specific facilities rather than a spatially replicated test of scale as a general factor; this constraint, and its consequences for interpretation, is discussed throughout. The objectives were to: (i) characterise indoor PM₁, PM_{2.5}, PM₁₀, CO₂, HCHO, TVOC, temperature, relative humidity, and air velocity across the three facilities and four meteorological seasons; (ii) statistically partition the variance in each parameter attributable to facility, season, and their interaction using two-way factorial ANOVA; (iii) benchmark measured concentrations, for indicative screening only, against WHO, Central Pollution Control Board, ASHRAE, and National Building Code reference values; and (iv) examine the process-level association of adhesive-pasting operations with short-term VOC and HCHO variation. The study characterises the indoor thermal environment (temperature, relative humidity, air velocity, and compliance with ASHRAE 55 reference bands) rather than modelling subjective occupant thermal comfort, since no occupant survey instrument was administered in this phase of the work.

Results

Descriptive overview

Table 3 summarises mean $\pm$ SD values for all nine measured parameters by facility. A consistent monotonic gradient (organized < MSME < cottage) was observed for every pollutant and for CO₂, with the inverse gradient for air velocity. Mean PM_{2.5} rose from 62.4 ± 28.9 $\mu\text{g}/\text{m}^3$ in the organized unit to 99.1 ± 40.4 $\mu\text{g}/\text{m}^3$ in the MSME unit and 126.0 ± 46.0 $\mu\text{g}/\text{m}^3$ in the cottage unit (2.02-fold organized-to-cottage increase). Mean CO₂ rose from 715.0 ± 68.6 ppm to 916.8 ± 115.0 ppm to 1358.8 ± 179.8 ppm across the same gradient (1.90-fold), while mean HCHO and TVOC increased 3.04-fold (0.096 to 0.292 ppm) and 3.53-fold (0.75 to 2.64 ppm), respectively. Mean occupied-zone air velocity fell from 0.81 ± 0.15 m/s in the organized unit to 0.42 ± 0.09 m/s in the MSME unit and 0.16 ± 0.05 m/s in the cottage unit.

Seasonal and between-facility patterns are visualised jointly in Figure 1 (boxplots) and Figure 2 (interaction plots for PM_{2.5} and CO₂). Particulate matter followed a marked seasonal cycle nested within the between-facility gradient, peaking in winter and post-monsoon and reaching a minimum in the monsoon season for all three facilities (Figure 1, Figure 3), consistent with the strong seasonal cycle of ambient particulate loading typical of the Indo-Gangetic Plain. CO₂, HCHO and TVOC, in contrast, showed comparatively flat seasonal profiles within each facility (Figure 1, Figure 2b), with the between-facility gradient preserved across all four seasons.

Two-way ANOVA: variance partitioning

Table 4 reports the full two-way ANOVA results (facility $\times$ season, Type III sum of squares; error df = 596 throughout). Facility was a statistically significant source of variance for every parameter (all $p < .001$) and was, by partial eta-squared, the dominant effect for six of the nine parameters: air velocity ($\eta^2_p = 0.866$), CO₂ ($\eta^2_p = 0.811$), HCHO ($\eta^2_p = 0.781$), PM₁₀ ($\eta^2_p = 0.696$), PM_{2.5} ($\eta^2_p = 0.710$), and PM₁ ($\eta^2_p = 0.691$), alongside a large effect on TVOC ($\eta^2_p = 0.574$). Season was a statistically significant and large-effect source of variance for the particulate matter fractions ($\eta^2_p = 0.813$ - 0.830) and for the thermal variables (temperature $\eta^2_p = 0.674$; relative humidity $\eta^2_p = 0.655$), but was not statistically significant for CO₂ ($F(3,596) = 1.19$, $p = .314$), HCHO ($F(3,596) = 0.09$, $p = .965$), TVOC ($F(3,596) = 0.12$, $p = .951$), or air velocity ($F(3,596) = 1.08$, $p = .358$). The facility $\times$ season interaction was statistically significant but modest for the particulate fractions ($\eta^2_p = 0.072$ - 0.086) and for relative humidity ($\eta^2_p = 0.028$), and was not significant for CO₂, HCHO, TVOC, air velocity, or temperature. Because η^2_p is not directly comparable across parameters with differing residual variances, “dominant” describes the observed sample rather than a formally ranked comparison (Methods).

Post-hoc comparisons and simple effects

Games-Howell post-hoc comparisons, Holm-corrected across the 27 pairwise tests spanning all nine parameters, confirmed that all three pairwise between-facility differences remained statistically significant ($p < .001$, $p_{\text{Holm}} < .001$) for PM₁, PM_{2.5}, PM₁₀, CO₂, HCHO, TVOC, and air velocity. For relative humidity, all three pairwise comparisons were also significant after correction (organized-MSME: -7.4 percentage points, $p < .001$, $p_{\text{Holm}} < .001$; organized-cottage: -14.0 points, $p < .001$, $p_{\text{Holm}} < .001$; MSME-cottage: -6.6 points, $p < .001$, $p_{\text{Holm}} < .001$). For temperature, the comparison between the organized-cottage and MSME-cottage was significant both before and after correction (-2.53 °C, $p = .002$, $p_{\text{Holm}} = .007$; respectively), but the comparison between the naturally ventilated cottage unit and MSME-cottage was not significant, before or after correction (-0.37 °C, $p = .872$, $p_{\text{Holm}} = .872$, respectively), suggesting that the mean temperature of the two mechanically-assisted facilities, despite differing ventilation strategies, was not statistically significantly different, but the mean temperature of the naturally ventilated cottage unit was significantly higher than the two mechanically-assisted units.

Simple-effects analysis (one-way ANOVA: facility in each season) was performed for every test (across the nine parameters and four seasons) and the p_{Holm} values confirmed that the between-facility gradient was statistically significant in all seasons for all pollutants and across the air velocity tests (all $p < .001$; partial η^2 ranging 0.55-0.88). For temperature, the between-facility effect was significant in every season but markedly weaker in summer ($F(2,137) = 3.51$, $p = .033$, $p_{\text{Holm}} = .033$, $\eta^2_p = 0.049$) than in winter ($F(2,185) = 17.17$, $p < .001$, $p_{\text{Holm}} < .001$, $\eta^2_p = 0.157$) or post-monsoon ($F(2,105) = 12.90$, $p < .001$, $p_{\text{Holm}} < .001$, $\eta^2_p = 0.197$); the summer effect was the single weakest result in either corrected family (still significant at $p_{\text{Holm}} = .033$, but only marginally so) and is consistent with extreme ambient summer heat in Agra narrowing the thermal gap between facilities regardless of ventilation strategy.

Screening against regulatory and guideline reference values

Because most thresholds, notably the WHO/NAAQS 24-hour PM standards, are defined over averaging periods far longer than the ten-minute sessions monitored here, we restrict formal threshold screening to the two parameters whose reference averaging period is reasonably comparable to a session mean: the WHO 30-minute HCHO guideline, and the ASHRAE 62.1/National Building Code CO₂ design criterion (a steady-state ventilation-adequacy benchmark under sustained occupancy, for which a session-mean exceedance indicates potential ventilation insufficiency rather than a formal non-compliance determination). CO₂ exceeded 1000 ppm in 0.0% (organized), 25.9% (MSME), and 99.5% (cottage) of sessions; HCHO exceeded the WHO guideline in 70.6% (organized), 100% (MSME), and 100% (cottage) of sessions (Table 5). PM₁, PM_{2.5}, PM₁₀ and TVOC concentrations are instead reported descriptively only (means in Table 3; distributions in Figure 1), without threshold screening, because their applicable guidelines specify averaging periods (24-hour for PM, no formally defined short-term TVOC limit in the standards consulted) that a ten-minute session mean cannot legitimately be compared against.

Thermal environment relative to ASHRAE 55

Compliance with the ASHRAE 55 seasonal indoor temperature band (23-26 °C summer; 20-24 °C winter) was low across all three facilities and both applicable seasons, but was particularly poor during summer: only 1.9% of organized-unit sessions, 0.0% of MSME sessions, and 0.0% of cottage-unit sessions fell within the 23-26 °C band (mean summer temperatures of 34.3, 35.3, and 37.3 °C, respectively), indicating that even the air-conditioned

organized facility did not maintain summer indoor temperatures within the ASHRAE band under Agra's extreme summer climate. Winter-band compliance was higher but still modest (organized 37.5%; MSME 34.6%; cottage 38.7%). Compliance with the ASHRAE 55 relative-humidity band (30-60%) was 55.7% (organized), 60.1% (MSME), and 45.7% (cottage). Occupied-zone air velocity fell below 0.20 m/s, the ASHRAE 55 reference value below which air movement provides negligible evaporative/convective cooling benefit, in 0.0% of organized-unit and MSME sessions but in 74.7% of cottage-unit sessions (Table 6), indicating that the cottage unit combined the highest mean temperature and humidity with the least air movement available to offset thermal load. Because none of the three facilities operated space heating, the ASHRAE 55 winter band is applied here only as a fixed reference envelope, not an expectation of attainable performance.

Indoor/outdoor relationship and process-level (pasting) effects

The session-level indoor/outdoor (I/O) PM_{2.5} ratio (Figure 5) increased across the between-facility gradient: 0.477 ± 0.093 (organized), 0.689 ± 0.106 (MSME), and 0.999 ± 0.269 (cottage). The organized facility's mechanical filtration and envelope control removed roughly half of the ambient particulate loading, whereas the cottage unit's indoor PM_{2.5} concentration was, on average, indistinguishable from the paired outdoor concentration, consistent with a substantial indoor source contribution (leather dust and adhesive aerosol) superimposed on outdoor infiltration. This inference assumes that the city-level ambient PM_{2.5} series used as the outdoor reference (Methods) reasonably approximates each facility's immediate outdoor air; because the three facilities are located in different parts of Agra and a single city-level series was applied to all of them, the I/O ratios reported here should be read as approximate estimates rather than facility-specific measurements, and this spatial mismatch is a limitation addressed further in the Discussion.

Adhesive-pasting operations were associated with a statistically significant elevation in session-mean TVOC across all three facilities (Welch's t-test on log₁₀-transformed TVOC: organized $t = 23.12$, $p < .001$; MSME $t = 15.93$, $p < .001$; cottage $t = 8.20$, $p < .001$), indicating pasting as an acute, process-level VOC source across facility types. HCHO showed no statistically significant association with the pasting indicator in the MSME ($p = .150$) or cottage ($p = .835$) facilities; in the organized facility the association approached but did not cross the conventional significance threshold ($p = .051$), which given the absence of correction for multiple comparisons across facilities and parameters (Methods) is better read as a borderline trend than as clear evidence of no association. We do not offer a chemical mechanism for this pattern, since no VOC or HCHO speciation data were collected and the composition of the adhesives used was not independently verified.

Correlation structure

Spearman correlations among the nine parameters (Figure 4) showed, as expected, very strong intercorrelation among the three particulate size fractions ($\rho = 0.99$ for all pairs). CO₂, HCHO and TVOC were moderately-to-strongly intercorrelated ($\rho = 0.71$ - 0.81), consistent with a shared dependence on ventilation rate and occupant/process density. All pollutants were negatively correlated with air velocity, most strongly for the gas-phase pollutants (CO₂: $\rho = -0.84$; HCHO: $\rho = -0.85$; TVOC: $\rho = -0.73$) and moderately for particulate matter ($\rho \approx -0.50$ to -0.51). With $n = 608$, correlations with $|\rho| > 0.13$ are statistically significant at $p < .001$ (two-tailed, uncorrected); the weakest associations reported in this dataset (e.g., temperature-air velocity, $\rho = -0.12$; CO₂-temperature, $\rho = 0.10$) remain nominally significant at the conventional $p < .05$ threshold ($|\rho| > 0.08$) but are practically weak, illustrating that at this sample size effect size, not the p-value, should carry the interpretive weight.

Discussion

The central empirical finding is the divergence between the determinants of particulate versus gas-phase indoor pollution in this occupational setting. Particulate matter and the thermal-environment variables were shaped jointly by between-facility differences and season, consistent with outdoor-infiltration-driven seasonal cycles widely reported for particulate matter in Indian and South Asian indoor environments [31,34-35]. CO₂, HCHO, TVOC and air velocity, by contrast, were governed almost entirely by between-facility differences ($\eta^2p = 0.57$ - 0.87) with no detectable seasonal signal, contrasting with school- and residential-building IAQ literature in which seasonal ventilation behaviour, such as window-opening, is often reported as a primary driver of indoor CO₂ and VOC variability [33,38]. A plausible explanation is that ventilation in all three facilities was governed by fixed infrastructure and continuous production activity rather than occupant-driven, season-dependent window operation, so that each facility's observed ventilation configuration, rather than ambient climate, is associated with the achievable dilution rate year-round; this interpretation is consistent with evidence that mechanical ventilation and process control are associated with indoor pollutant concentration independent of outdoor conditions [32,39]. This attribution to ventilation is an inference from facility characteristics (fan, air-conditioning, and exhaust configuration) rather than a measured causal pathway: ventilation rates (air changes per hour) were not measured directly in this study, so the term "ventilation infrastructure" should be read as a plausible but unconfirmed proxy throughout this Discussion, not as a demonstrated mechanism. Because this is also a single-facility-per-tier design, between-facility differences cannot be statistically separated from other unmeasured, facility-specific characteristics that may also contribute to this pattern, and the finding should be read as an association among these three facilities rather than a demonstrated causal effect of scale.

The magnitude of the between-facility exposure gradient, CO₂ above 1000 ppm in 99.5% of cottage-unit sessions and HCHO above the WHO 30-minute guideline in all MSME and cottage sessions, indicates elevated exposure during working hours for MSME and cottage-unit workers, who together form the numerical majority of India's leather footwear workforce. This extends the limited occupational literature on the sector, which has documented respiratory microplastic burden among shoe manufacturing workers [25], oxidative stress linked to VOC exposure [26], and elevated occupational health risk among leather tannery workers [29], by adding a quantitative, standards-referenced IAQ comparison across the organized-MSME-cottage gradient within leather footwear manufacturing specifically. The consistency of pasting-linked TVOC elevation across all three facilities reinforces prior links between footwear manufacturing conditions and worker exposure [27-28], and points to point-source engineering control at the pasting bench, rather than general dilution ventilation alone, as a directly actionable intervention [40-41]. Working hours, employee density, and production volume were not systematically recorded in

this study; if MSME and cottage-tier workers work longer hours than their organized-sector counterparts, cumulative exposure would be higher still than the session-level concentration differences alone indicate, a compounding factor that merits direct examination in future work.

Even the air-conditioned organized facility achieved ASHRAE 55 summer temperature-band compliance in only 1.9% of sessions, reflecting the severity of Agra's summer climate relative to typical air-conditioning design capacity in Indian small-manufacturing settings, a pattern broadly consistent with reports that comfort provision in Indian buildings falls short of ASHRAE 55 static bands even where cooling is installed [19,22-23], and with the adaptive-comfort premise that static bands derived largely from temperate-climate studies [42] require regional recalibration for hot climates such as Agra's [43-44]. Elevated indoor humidity, most pronounced in the cottage unit during the monsoon season, further compounds this thermal burden [45]. More striking is the compounding of high temperature, high humidity, and minimal air movement in the cottage unit, where 74.7% of sessions registered air velocity below the ASHRAE 55 reference value for meaningful convective/evaporative cooling. Because air movement is a primary low-cost mechanism for extending the upper bound of thermal acceptability in naturally ventilated, non-air-conditioned spaces [46-47], the near-static air observed in the cottage unit plausibly compounds, rather than merely coincides with, its already elevated temperature and humidity, and may elevate heat-stress risk for workers beyond what temperature alone would indicate. This parallels adaptive-comfort evidence from other naturally ventilated Indian contexts emphasising air movement as a low-cost thermal-relief strategy in the absence of mechanical cooling [18,21], and suggests that low-cost interventions such as additional ceiling or pedestal fans, considerably cheaper than air conditioning, could meaningfully improve thermal conditions in the cottage-scale unit even without addressing the pollutant burden directly.

The systematic increase in the I/O PM_{2.5} ratio from 0.48 (organized) to 1.00 (cottage) is consistent with a shift in the dominant exposure pathway across the between-facility gradient: the organized facility's filtration and envelope control appear to achieve substantial removal of outdoor-infiltrated particulate matter, consistent with intervention evidence on filtration effectiveness elsewhere [48-49], while the cottage unit's I/O ratio near unity is consistent with indoor sources, such as leather dust and adhesive aerosol, contributing a particulate load comparable to the ambient background. As noted in Results, this inference rests on a city-level ambient PM_{2.5} series rather than a facility-specific outdoor sensor and should be treated as indicative rather than definitive; a co-located outdoor sensor at each site would allow more precise indoor-source attribution in future work. With that caveat, the pattern has a practical implication: in the cottage tier, outdoor-air filtration alone would likely be insufficient, and interventions should additionally target indoor source control, such as wet cutting or point-source pasting exhaust, rather than dilution ventilation or outdoor-air filtration in isolation.

This is, to our knowledge, among the first studies to apply a factorial (facility by season) field design to characterise IAQ and thermal-environment quality across the organized-MSME-cottage scale gradient within India's leather footwear manufacturing sector. Its central limitation, stated plainly, is that each scale tier is represented by a single facility: the between-session variance captured by the ANOVA reflects temporal replication within each facility, not spatial replication across facilities of the same tier, so between-facility differences here cannot be statistically disentangled from other unmeasured, facility-specific characteristics, such as layout, production volume, employee density, management practice, or building age, that covary with scale. The findings should accordingly be read as hypothesis-generating evidence from a three-facility case study, not as confirmed proof of a general scale effect, even though the direction of the pattern is consistent with established building-science principles linking ventilation infrastructure to indoor pollutant concentration [32-33]. The sensors used were deployed and operated as supplied by the manufacturer; no independent field calibration against a reference instrument was performed during the study, and the three units were not cross-checked against one another at a common location, so a fixed, facility-specific measurement bias cannot be ruled out and would be indistinguishable, in this design, from a genuine between-facility difference. A simple sensitivity check indicates how large such a bias would need to be to account for the observed gradient on its own: eliminating the organized-cottage difference by instrument bias alone would require the cottage sensor to over-read (or the organized sensor to under-read) by approximately 50% for PM_{2.5}, 47% for CO₂, 67% for HCHO, and 72% for TVOC, while the smaller organized-MSME contrasts would require biases of roughly 22-53% depending on parameter (see Methods for the calculation). These magnitudes exceed the typical 10-20% accuracy specification of uncalibrated low-cost sensors for the larger cottage-tier contrasts, which are accordingly more robust to plausible instrument bias, but the smaller organized-MSME gaps, particularly for CO₂, fall within a plausible bias range and should be interpreted with corresponding caution; without cross-calibration, the reported between-facility differences may include some contribution from instrument-specific bias, and the findings should be treated as provisional pending calibration-verified measurement. Similarly, whether each pasting event was identified through direct observation or inferred from concurrent readings was not separately documented in the field records retained for this analysis; because the recording protocol cannot be confirmed from the retained documentation, the pasting-TVOC association reported here should be treated as exploratory rather than confirmatory, and the possibility that pasting events were in practice identified partly from concurrent TVOC elevation, which would make the association partly definitional rather than fully independent, cannot be ruled out. Ten-minute session means were compared, for screening purposes only, against thresholds defined over longer averaging periods where the averaging period was reasonably comparable (Results); this is not a substitute for continuous 24-hour monitoring, which future work should incorporate. This study characterises the objective thermal environment rather than subjective thermal comfort or perceived air quality, since no occupant survey was administered; incorporating such surveys, and worker demographic characteristics such as sex, age, and body mass index that are known to modulate thermal response [50-51], is a natural extension. Outdoor reference values were drawn from a city-level ambient source rather than an on-site sensor at each facility, which may introduce spatial mismatch in the I/O ratios discussed above. The 27-month monitoring period spanned two winters and two summers and does not capture inter-annual variability, and the panel did not include ozone, nitrogen dioxide, VOC speciation, or PM chemical composition, each of additional occupational health relevance.

With these caveats, the findings from these three facilities are consistent with ventilation infrastructure and point-source exhaust control, rather than seasonal or climatic factors, as plausible primary levers for improving occupational indoor environmental quality in India's leather footwear sector. The consistency of these findings with established building-science principles suggests that scale-differentiated regulatory or extension-service mechanisms, such as subsidised local-exhaust retrofits or low-cost ventilation fans targeted at MSME and cottage-tier units that fall largely outside the inspection and licensing regime applied to registered factories [24,30], merit investigation in larger, multi-facility studies; the present three-facility design does not itself constitute evidence sufficient to inform policy change. Future work should extend this design across multiple cities and multiple facilities per scale tier so that scale can be statistically distinguished from other facility-specific characteristics, incorporate subjective occupant thermal comfort and IAQ perception

assessment, measure ventilation rates directly, cross-calibrate instruments before deployment, and evaluate low-cost point-source ventilation retrofits through pre-post intervention monitoring.

Methods

Study area and facilities

Field monitoring was conducted at three leather footwear manufacturing units located in established leather-manufacturing localities of Agra, Uttar Pradesh, India: Sector-3, Sikandra Industrial Area (organized unit); Hing ki Mandi (MSME unit); and the Mughal Road/Nai ki Mandi locality (cottage unit). The three units were purposively selected to represent the three scale tiers recognised in India's Micro, Small and Medium Enterprises classification framework, each with materially different ventilation infrastructure. The organized unit (200+ employees) is an air-conditioned manufacturing hall with mechanical exhaust ventilation, dedicated fume hoods over the pasting station, a physically separated pasting cabin, compulsory personal protective equipment, and local dust collection at cutting and lasting stations. The MSME unit (51-200 employees) is a naturally ventilated hall, provided with pedestal and wall mounted fan and two roof mounted ridge ventilators and partial local exhaust at the pasting bench and an open production layout. The cottage unit (5-50 employees) is a one room workshop that is situated within a residential building and is ventilated only by ceiling and table fans, and pasting and stitching take place in the same room.

Each scale item is a single facility, so the comparisons between groups that follow reflect differences between the three specific facilities, and not a spatially replicated scale effect. The differences observed between these three facilities are considered to reflect a set of characteristics that are correlated with one another, such as employee density, scale, floor area, production volume, and typical working hours, but were neither measured nor controlled; between-facility differences in these characteristics may be interpreted as differences in ventilation infrastructure, which was a plausible but potentially unconfirmed contributor (Discussion). Air changes per hour were not measured directly, but rather determined by the observed fan, air conditioning and exhaust arrangement at each facility. This is referred to as the "between-facility gradient" henceforth. Agra's ambient air quality is markedly seasonal, with particulate levels typically highest in winter and lowest during the monsoon, consistent with the broader climatology of the Indo-Gangetic Plain and with the indoor particulate-matter seasonality reported in Results.

Instrumentation

Indoor PM₁, PM_{2.5} and PM₁₀ ($\mu\text{g}/\text{m}^3$), CO₂ (ppm), HCHO (ppm), TVOC (ppm), temperature ($^{\circ}\text{C}$) and relative humidity (%) were logged at one-minute resolution using a Prana Air Cair+ multi-sensor indoor air quality monitor (laser light-scattering particulate sensor; non-dispersive infrared CO₂ sensor; electrochemical HCHO sensor; photoionisation/metal-oxide TVOC sensor). Occupied-zone air velocity (m/s) was measured with a MECO 961P vane anemometer (range 1-25 m/s; resolution 0.01 m/s; accuracy $\pm(3\%$ of reading ± 0.2 m/s)) at three fixed stations per session. Both instruments were operated as supplied by the manufacturer: no independent field calibration against a reference-grade analyser was performed during the study, and the units were not cross-checked against one another at a common location prior to or during deployment. This is a limitation of the present design (Discussion), and the reported concentrations should be interpreted as measurements from this specific instrument pairing rather than as independently calibration-verified absolute values. The use of compact, continuously-logging optical and electrochemical sensors for occupational and indoor-air field campaigns of this kind is well established in the low-cost sensor literature [52-53], which also documents the accuracy trade-offs of such instruments relative to reference-grade analysers [54].

Sampling design

Monitoring was conducted over a 27-month period from 1 December 2023 to 24 February 2026. Two visit-days per active week were scheduled at random within the Monday-Saturday working week, with occasional single- or double-week skips to reflect realistic fieldwork constraints; Sundays and observed national and Uttar Pradesh public holidays were excluded from sampling. On each visit day, one or two of the three facilities were monitored, with two ten-minute monitoring sessions per facility separated by at least 60 minutes and conducted between 09:30 and 18:30. Each session yielded approximately ten one-minute indoor readings and three spot air-velocity readings. Whether each session coincided with an active adhesive-pasting operation was recorded as a binary per-session indicator (pasting event: yes/no); the specific recording protocol (direct observation versus inference from concurrent readings) was not separately documented, event duration and timing within the session were not logged, and adhesive brand or formulation was not recorded beyond the general use of solvent-based contact adhesives across all three facilities, so the process-level analysis reflects association with session-level pasting activity rather than a time-resolved or chemically speciated exposure profile (Discussion). Paired outdoor reference readings (air quality index, PM_{2.5}, temperature, relative humidity) for each indoor session were obtained from the AQI.in public ambient air-quality dashboard for Agra (<https://www.aqi.in/dashboard/india/uttar-pradesh/agra>), which aggregates city-level monitoring data, rather than from a dedicated on-site sensor at each facility; because a single city-level series was applied across all three facilities, facility-specific outdoor conditions could not be resolved, and this spatial mismatch is addressed in the Discussion.

Minute-resolution readings were aggregated to session means, the unit of statistical analysis, by facility, date, and session number. After aggregation, 608 valid sessions were retained: 194 in the organized unit, 228 in the MSME unit, and 186 in the cottage unit (Table 1). No sessions contained missing values in any analysed parameter following aggregation.

Parameters and reference benchmarks

Measured concentrations were benchmarked, for indicative screening only, against applicable WHO, Central Pollution Control Board, ASHRAE, and National Building Code of India guideline or standard values (Table 2). Session means (ten-minute averages) are compared against these threshold values for indicative screening purposes only; direct compliance determination requires averaging over the full regulatory reference period, which was outside the scope of the present short-session sampling protocol (Discussion). These reference values span health-based exposure guidelines, prescriptive ventilation-design standards, and comfort-based environmental bands; they are not interchangeable in regulatory status and are reported together only for indicative screening against benchmarks widely used in the Indian and international literature. The TVOC indicative value of ≤ 0.3 ppm follows the German AGÖF orientation value for total volatile organic compounds in indoor air; we did not identify a verifiable, independently confirmed TVOC threshold in the ISHRAE Indoor Environmental Quality Standard 2019 and therefore do not attribute this value to that standard.

Statistical analysis

All analyses were performed in Python 3.10 using pandas (2.3.3), SciPy (1.15.3), statsmodels (0.14.6), and pingouin (0.6.1). Pollutant concentrations (PM₁, PM_{2.5}, PM₁₀, CO₂, HCHO, TVOC) and air velocity are strictly positive and right-skewed; all six variables were log₁₀-transformed prior to inferential analysis. Temperature and relative humidity were analysed on their raw scale. Normality of residuals was assessed via the Shapiro-Wilk statistic and homogeneity of variance via Levene's test. The two-way factorial, facility x season, Type III sum of squares ANOVA was retained as the primary model following the robustness analysis of this model under large, yet not equal, cell sizes ($n = 30$ -78; Table 1) [36]. The Games-Howell method, which is suitable for use with unequal variances and unequal group sizes, was used for post-hoc comparisons and Holm-Bonferroni correction was applied for each family of pairwise comparisons (27 pairwise comparisons across the nine parameters) to control the family-wise error rate; raw p values are reported in Results with corrected p values (p_{Holm}). Effect sizes (partial eta-squared, η^2_p ; Cohen's benchmarks: small ≈ 0.01 , medium ≈ 0.06 , and large ≥ 0.14) are reported here and are not directly comparable across parameters with differing residual variances, so cross-parameter comparisons in Results are reported descriptively. Simple effects (facility differences within each season) were explored using one-way ANOVA with each season as a strata; this series of 36 tests (nine parameters x four seasons) were also Holm-corrected. The interaction effects ($\eta^2_p \approx 0.02$ -0.03) were not the subject of a separate corrected family and warrant cautious interpretation given their modest magnitude. Pasting effects on TVOC and HCHO were assessed with Welch's t-test on log-transformed session means; the I/O PM_{2.5} ratio was computed per session; associations among parameters used Spearman correlation. As a post-hoc sensitivity check on the between-facility differences (Discussion), we estimated, for each parameter, the uniform relative sensor bias (1 - low-facility mean / high-facility mean) that would need to be present in a single direction to fully account for each pairwise facility contrast in Table 3, absent any true underlying difference; this is a simple bounding calculation on the reported means, not a formal statistical test, and does not itself estimate actual instrument bias. Significance was set at $\alpha = 0.05$ throughout.

Declarations

Data availability

The anonymised dataset has now been deposited in the Zenodo repository and is publicly accessible at <https://zenodo.org/records/22765221?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjE1Mjc5ZjEyLWQ0ZjktNGQyNi00ZjUyLWZmY2I4Y2MzMGM1NiIsImRhdGEiOiNt9LCJyYW5kb20iOiI3NzJiMTBIZTAzMzI0MSEj9503bgCVmAPEKzYw>. All information that could identify the participating facilities or individual workers has been removed.

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Author contributions

Mohd Arif- Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing - original draft and review and editing. Rajendra Yadav- Conceptualization, Writing - review and editing. Sujoy Kumar Dey: Supervision, Writing - review and editing. Shailendra Singh- Supervision, Resources, and editing. All authors read and approved the final manuscript.

Competing interests

The authors declare no financial or non-financial competing interests.

Ethics statement

This study involved non-invasive environmental monitoring only; no employee health data, biological samples, or personally identifiable information were collected, and no occupant survey was administered. Non-invasive environmental monitoring of this kind did not require formal ethics committee review under institutional policy; informed consent for monitoring access was obtained from the management of each participating facility.

Consent to participate

Informed consent was obtained from all participants prior to data collection, that participation was voluntary, and that responses were recorded anonymously.

Consent to publish

"Not applicable" as the manuscript does not contain any individual person's identifying data, including images, videos, voice recordings or personal details.

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Tables

Table 1. Distribution of monitoring sessions by facility and season.

Facility	Winter	Summer	Monsoon	Post-monsoon	Total
Organized (Ltd. Company)	48	54	54	38	194
MSME	78	46	64	40	228
Cottage	62	40	54	30	186
Total	188	140	172	108	608

Note. Season assigned by calendar month following the standard Indian Meteorological Department convention: Winter (December-February), Summer (March-May), Monsoon (June-September), Post-monsoon (October-November).

Table 2. Regulatory and guideline reference values used for benchmarking.

Parameter	Guideline / standard	Limit / range	Source
PM2.5 (24-h)	WHO Air Quality Guidelines 2021	15 µg/m ³	WHO (2021)
PM2.5 (24-h)	NAAQS India	60 µg/m ³	CPCB, NAAQS 2009
PM10 (24-h)	NAAQS India	100 µg/m ³	CPCB, NAAQS 2009
CO2	ASHRAE 62.1 / Indian National Building Code	<=1000 ppm (~700 ppm above outdoor)	ASHRAE 62.1-2022; NBC 2016, Part 8 Section 3
HCHO	WHO indoor air quality guideline	0.08 ppm (100 µg/m ³ , 30-min)	WHO (2010)
TVOC	German AGOF orientation value	<=0.3 ppm (~1 mg/m ³) acceptable	AGOF; no independently confirmed ISHRAE threshold identified (see Methods)
Indoor temperature (ASHRAE 55/ISHRAE)	ASHRAE 55 / ISHRAE	23-26°C summer; 20-24°C winter	ASHRAE 55-2020; ISHRAE IEQ 2019
Indoor relative humidity	ASHRAE 55	30-60%	ASHRAE 55-2020
Occupied-zone air velocity	ASHRAE 55	<=0.20 m/s (winter); <=0.25 m/s (summer), without local control	ASHRAE 55-2020

Note. These threshold values are used as indicative screening values only, and are not intended to be directly compared to session mean (10-minute averages); they should only be compared to session mean values for the purpose of direct compliance determination, which requires averaging over the full regulatory reference period (e.g., 24-h for PM standards) and was not within the scope of the present short-session sampling protocol (see Methods). Both the ASHRAE 62.1 CO2 criterion and an independent threshold are shown in one combined row for NBC 2016, which does not specify an independent threshold. Not interchangeable in terms of regulatory status, these reference values are grouped together for indicative screening only: they encompass health-related exposure levels (WHO, CPCB/NAAQS), prescriptive ventilation design levels (ASHRAE 62.1, National Building Code), or comfort-related environmental bands (ASHRAE 55, ISHRAE IEQ 2019).

Table 3. Descriptive statistics (mean +/- SD) of indoor air quality and thermal environment parameters by facility (n = 608 sessions).

Parameter	Organized (n = 194)	MSME (n = 228)	Cottage (n = 186)
PM1 (µg/m ³)	38.1 +/- 17.7	61.0 +/- 25.5	77.9 +/- 28.8
PM2.5 (µg/m ³)	62.4 +/- 28.9	99.1 +/- 40.4	126.0 +/- 46.0
PM10 (µg/m ³)	78.2 +/- 36.6	124.2 +/- 50.8	157.2 +/- 57.8
CO2 (ppm)	715.0 +/- 68.6	916.8 +/- 115.0	1358.8 +/- 179.8
HCHO (ppm)	0.096 +/- 0.03	0.183 +/- 0.04	0.292 +/- 0.05
TVOC (ppm)	0.75 +/- 0.42	1.58 +/- 0.59	2.64 +/- 0.75
Temperature (°C)	28.9 +/- 7.4	29.3 +/- 7.7	31.5 +/- 7.2
Relative humidity (%)	45.2 +/- 16.6	52.6 +/- 14.8	59.2 +/- 16.0
Air velocity (m/s)	0.81 +/- 0.15	0.42 +/- 0.09	0.16 +/- 0.05

Table 4. Two-way ANOVA results (facility x season, Type III sum of squares) for indoor air quality and thermal environment parameters.

Parameter	Industry F(2,596)	Industry p	Industry eta2p	Season F(3,596)	Season p	Season eta2p	Interaction F(6,596)	Interaction p	Interaction eta2p
PM1	665.19	<.001	0.691	860.67	<.001	0.813	7.75	<.001	0.072
PM2.5	729.29	<.001	0.710	970.10	<.001	0.830	9.08	<.001	0.084
PM10	683.46	<.001	0.696	923.42	<.001	0.823	9.38	<.001	0.086
CO2	1275.73	<.001	0.811	1.19	.314	0.006	2.19	.043	0.022
HCHO	1065.16	<.001	0.781	0.09	.965	0.0005	0.26	.954	0.003
TVOC	401.70	<.001	0.574	0.12	.951	0.0006	0.49	.814	0.005
Air velocity	1924.19	<.001	0.866	1.08	.358	0.005	0.44	.852	0.004
Temperature	33.94	<.001	0.102	410.19	<.001	0.674	1.04	.395	0.010
Relative humidity	81.50	<.001	0.215	377.54	<.001	0.655	2.84	.010	0.028

Note. ANOVA performed on log10-transformed values for PM1, PM2.5, PM10, CO2, HCHO, TVOC, and air velocity; raw values for temperature and relative humidity. eta2p = partial eta-squared. Error df (constant across effects) = 596 throughout.

Table 5. Screening comparison of session-mean CO2 and HCHO concentrations against reference thresholds whose averaging period is reasonably comparable to a 10-minute session mean, by facility.

Parameter (threshold)	Organized	MSME	Cottage	Mean Org.	Mean MSME	Mean Cott.
CO2 > 1000 ppm (ASHRAE 62.1 / NBC)	0.0%	25.9%	99.5%	715.0	916.8	1358.8
HCHO > 0.08 ppm (WHO, 30-min)	70.6%	100.0%	100.0%	0.096	0.183	0.292

Note. Session means (10-minute averages) are compared against thresholds defined over longer regulatory periods (Table 2; Methods). The WHO 30-minute HCHO guideline is averaging-period-comparable to a session mean. The ASHRAE 62.1/NBC CO2 threshold (1000 ppm) is a steady-state ventilation-design criterion, not a short-term exposure limit; session-mean exceedances indicate potential ventilation insufficiency only, not definitive non-compliance. PM1, PM2.5, PM10 and TVOC are deliberately excluded from this table because their applicable guidelines are defined over averaging periods (24-hour for PM; no formally defined short-term limit for TVOC in the standards consulted) too dissimilar from a ten-minute session mean for a screening comparison to be meaningful; their descriptive means are reported in Table 3 and distributions in Figure 1.

Table 6. Thermal environment relative to ASHRAE 55 reference bands, by facility.

Metric	Organized	MSME	Cottage
% sessions within 23-26°C (summer)	1.9%	0.0%	0.0%
% sessions within 20-24°C (winter)	37.5%	34.6%	38.7%
% sessions within 30-60% RH	55.7%	60.1%	45.7%
Mean air velocity (m/s)	0.81	0.42	0.16
% sessions with air velocity < 0.20 m/s	0.0%	0.0%	74.7%

Figures

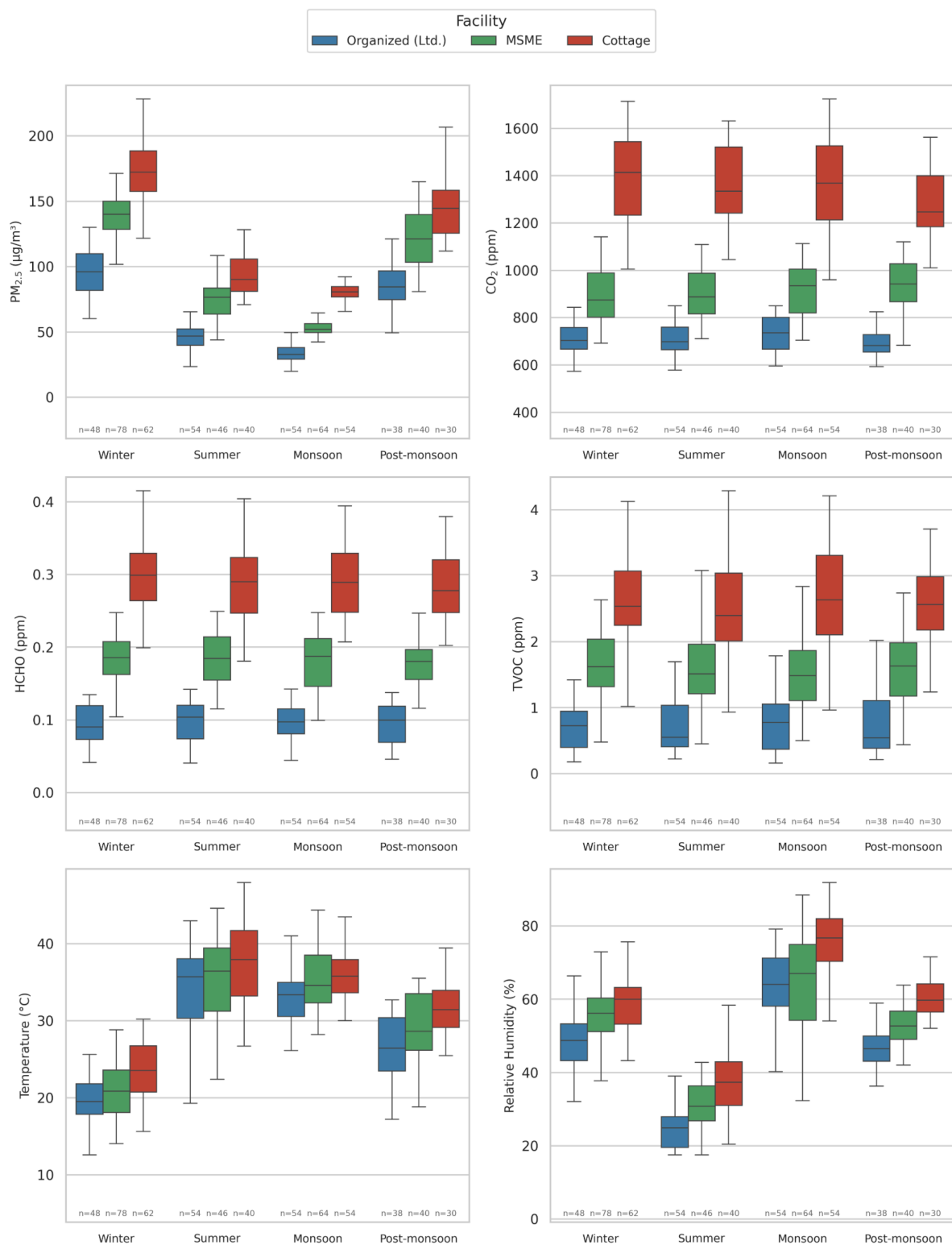


Figure 1

Distribution of PM_{2.5}, CO₂, HCHO, TVOC, temperature and relative humidity by facility and season (boxplots; whiskers to 1.5x IQR extending to the most extreme non-outlier value, outliers beyond the whiskers excluded from the plotted points for visual clarity). Cell sizes (facility x season) ranged from n = 30 (cottage, post-monsoon) to n = 78 (MSME, winter); see Table 1 for the full breakdown and the annotated n beneath each box.

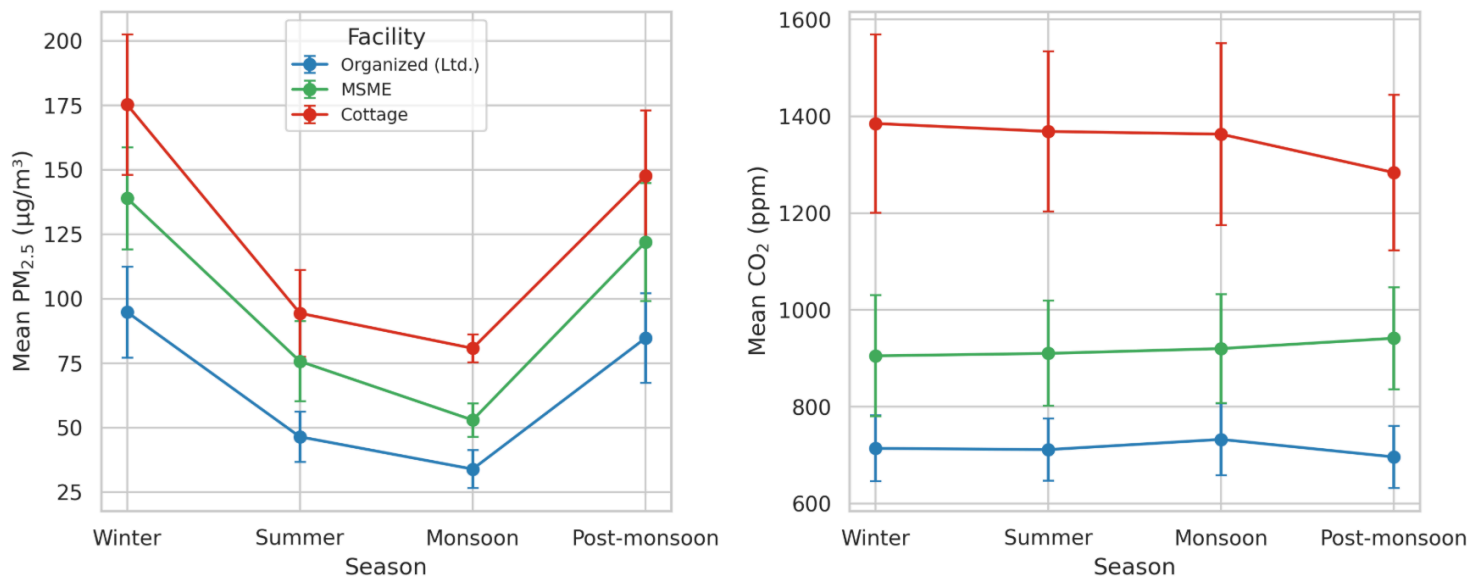


Figure 2

Facility x season interaction plots (mean $\pm$ SD) for (a) PM_{2.5} and (b) CO₂.

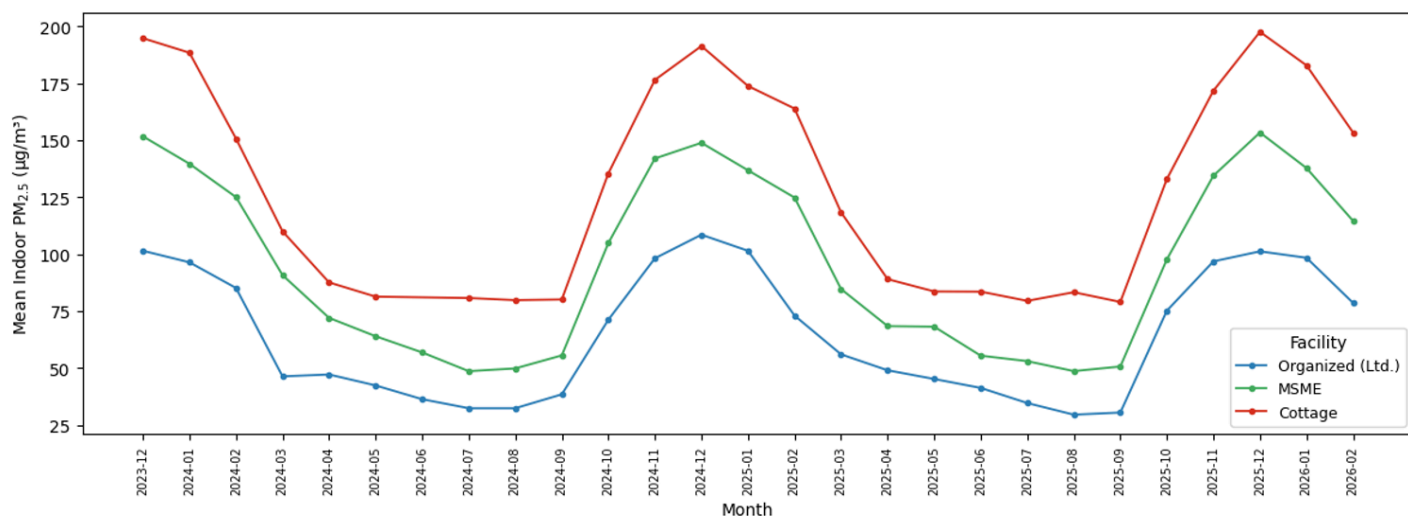


Figure 3

Monthly mean indoor PM_{2.5} by facility, December 2023-February 2026, shown descriptively; consistent with the exclusion of PM from formal threshold screening (Results, Table 5), no compliance reference lines are shown.

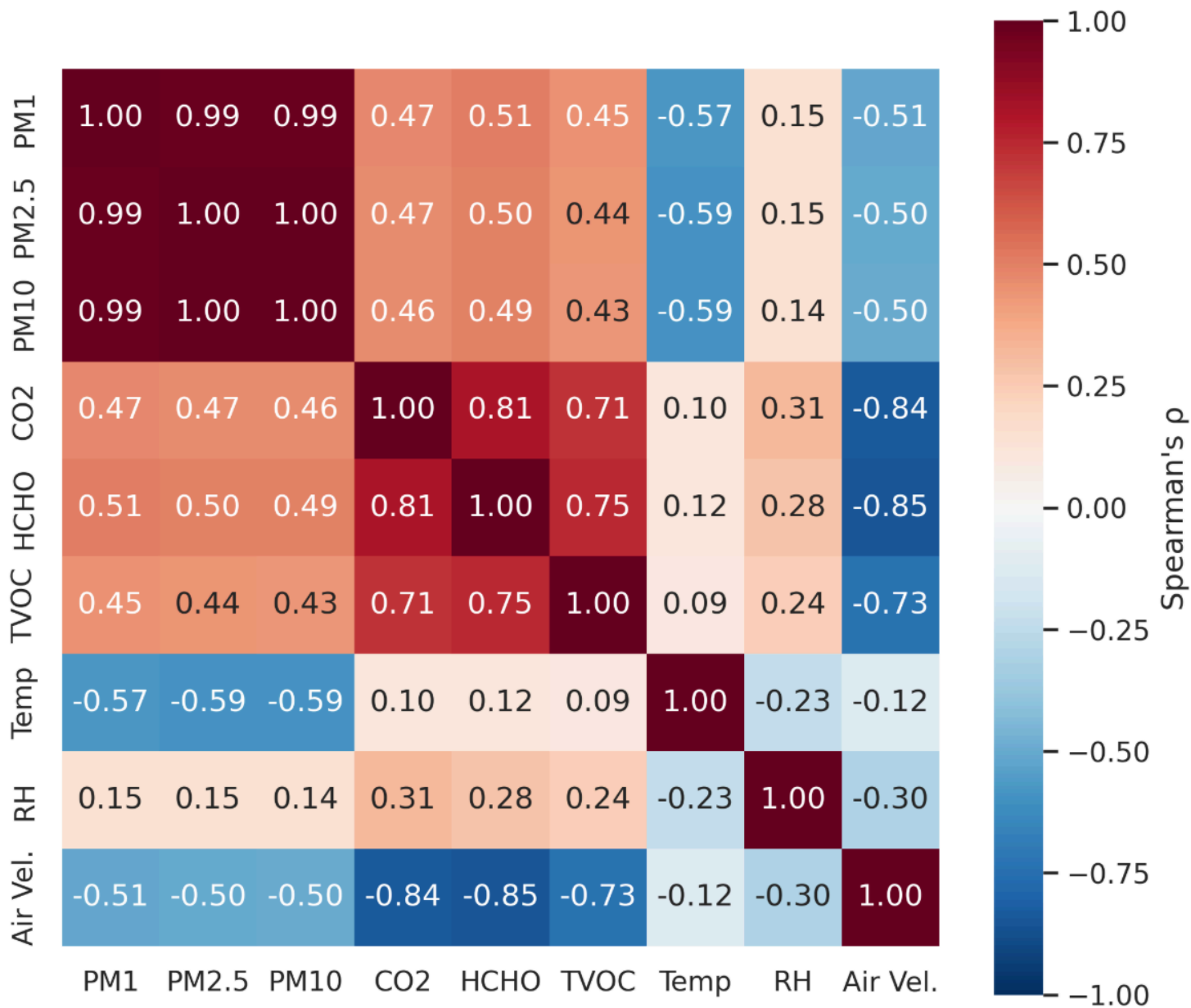


Figure 4

Spearman rank correlation matrix among indoor air quality and thermal environment parameters ($n = 608$ sessions). All coefficients with $|\rho| > 0.11$ are significant at $p < .001$ after Bonferroni correction for 36 pairwise comparisons; coefficients below this magnitude should be interpreted with caution regardless of nominal p -value.

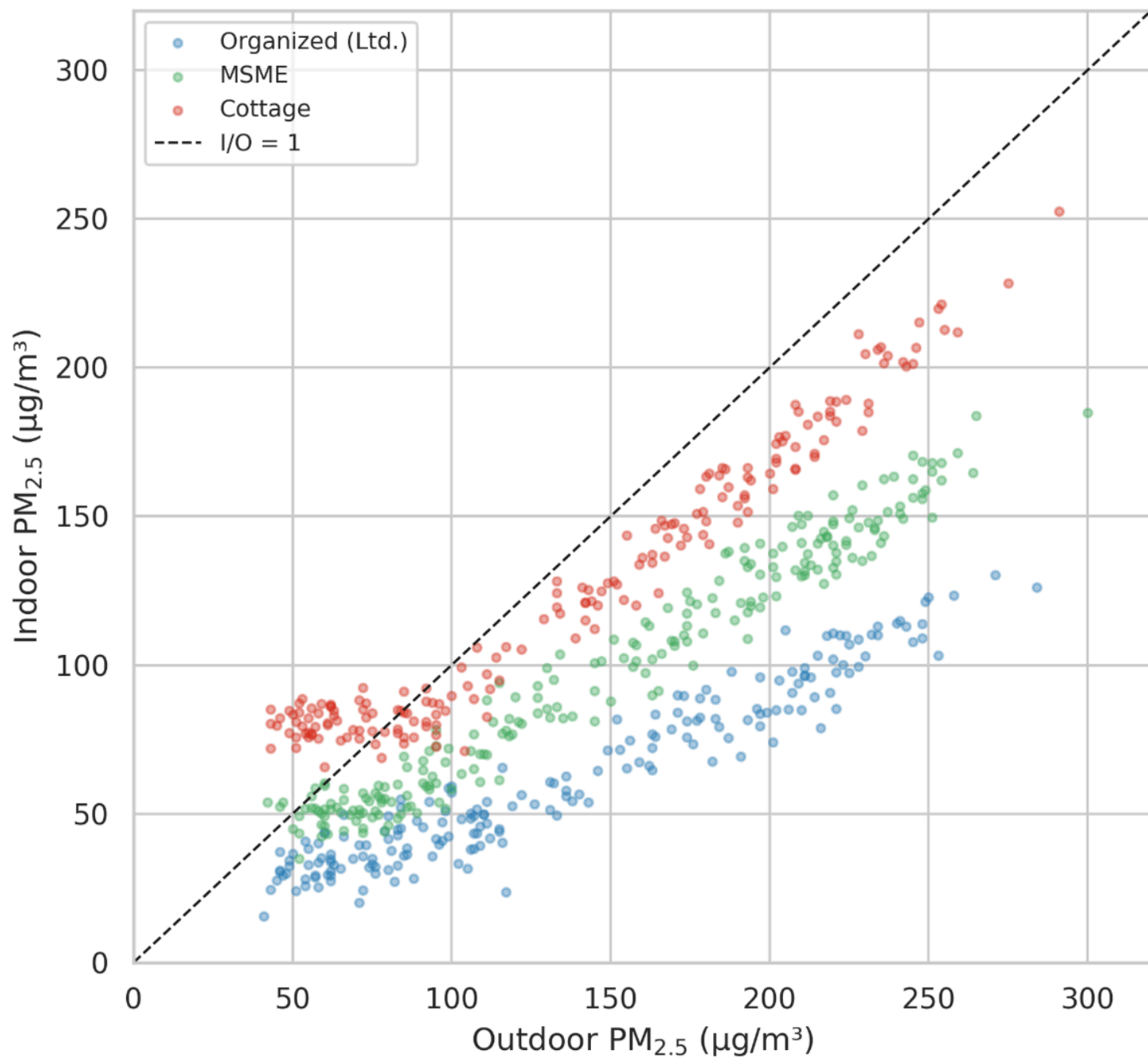


Figure 5

Session-level indoor vs outdoor PM_{2.5} by facility, with the indoor/outdoor = 1 reference line. Outdoor PM_{2.5} values are from a city-level ambient monitoring source (AQI.in) rather than a facility-specific on-site sensor and may not reflect each facility's immediate outdoor conditions (see Methods, Discussion).

Supplementary Files

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