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Ventilation, indoor air quality and thermal comfort in India's leather footwear manufacturing cluster: a tier-resolved field study

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Abstract

Footwear manufacturing in India is carried out in establishments of very different size, from formal factories to single rooms in converted houses, yet the air these workers breathe for nine to ten hours a day has not been compared across them. Air temperature, mean radiant temperature, relative humidity, air velocity, CO2, total volatile organic compounds (TVOC), formaldehyde and particulate matter measurements were taken at the breathing zone in three of the enterprise tiers of the Agra cluster, with each measurement coinciding with a simultaneous ASHRAE 55 ballot. The campaign resulted in 378 valid worker-session records in four seasons and 147 days. Ambient air standards from India, WHO guideline values and occupational exposure limits were used to compare concentrations. All of the pollutants increased in a linear fashion from large to cottage scale, and air velocity decreased from 0.80 to 0.16 m s − 1 and accounted for 79% of the variance in pollutant levels between the tiers. With CO2 fixed, the air velocity was also independently and negatively associated with TVOC and apparent formaldehyde, indicating that the gradient is driven by dilution and not by occupancy. 91.3% of sessions had apparent formaldehyde levels above the ACGIH TLV and all sessions in the two smaller tiers were also above the ACGIH TLV; no session anywhere was below the WHO PM2.5 guideline. Air movement was not related to outside temperature, but dropped considerably when adhesive was being applied, thus emission and dilution were inversely related at that time. The organising variable is enterprise size for occupational exposure in this sector, through the means of ventilation.

1. Introduction

Indoor air is now recognised as a determinant of health in its own right rather than a diluted version of what is outside (Morawska et al., 2022; Saini et al., 2020). Where that space is also a workplace the exposure is neither brief nor incidental, since a worker may spend well over two thousand hours a year in one room whose air is shaped by the materials handled, the machinery running, the number of people present and whatever air exchange the building allows.

Two literatures meet at this point. Studies of indoor air quality have shown how volatile organic compounds, formaldehyde and fine particles accumulate when emission is strong and dilution weak (Villanueva et al., 2022; Bousiotis et al., 2023; Feng et al., 2023), and how they relate to symptom reporting and respiratory outcome (Syazwan et al., 2012; Wolkoff, 2018; Roh et al., 2021; Nimlyat et al., 2023). Studies of thermal comfort have shown that occupants of naturally ventilated buildings depart systematically from steady-state heat balance predictions, the more so in warm climates (Brager et al., 2015; Manu et al., 2016; Rijal et al., 2019). One variable governs both: opening a building to dilute what is emitted inside admits the heat outside, and closing it against the heat concentrates the emission. Several authors have accordingly treated the two as a single optimisation (Che et al., 2019; Jia et al., 2021; Coggins et al., 2022; Martínez-Comesaña et al., 2022).

That combined work has been done almost entirely in schools, offices, dwellings and institutional buildings (Mendes et al., 2013; Papadopoulos et al., 2020; Korsavi et al., 2021; Cabovská et al., 2022;

Reda et al., 2022; Wang and Norbäck, 2022), with industrial settings far less studied beyond a refinery (Abdullah et al., 2018) and waterpipe cafés (Rostami et al., 2020). Seseña et al. (2022), in university training laboratories, showed how sharply pollutant profiles differ by activity and how little natural ventilation achieves, and that logic applies with more force where the activity is production and lasts a full shift.

India's leather and footwear sector illustrates the problem. It supports several million workers and is structurally fragmented across a few organised factories, a larger population of small and medium enterprises, and a very large number of household-scale workshops (CLRI, 2022; IBEF, 2023). Agra is one of the major clusters. All of the tiers are processed in the same way: cut and stitched uppers, bonded to the soles with solvent-based glue and lasted, finished and packed. There are no two buildings alike: a factory hall with roof monitors and extraction, and a ten-square-metre room with one window, work is determined by identical conditions, but under completely different dilution.

The most important step in this process is the cementing. The solvents used to dissolve the neoprene and polyurethane adhesives will flash off during application and drying, and the skins used in the adhesives and leathers may release formaldehyde as well (Qin et al., 2020; Villanueva et al., 2022); leather and sole dust is generated from clicking, skiving, buffing and polishing. Baeza-Martínez et al. (2022) recovered environmental microplastics from the lower airway of shoe manufacturing workers, establishing that material generated in these rooms reaches the deep lung, while Kanti Deb et al. (2018) documented noise, heat and lighting stress among Bangladeshi footwear workers and Chuenyindee et al. (2022) linked perceived conditions to quality and retention. What nobody has established is how exposure varies with establishment size when process, cluster and outdoor airshed are held constant.

The thermal side is equally thinly covered. Naturally ventilated Indian buildings sustain comfort well above the temperatures implied by international standards (Indraganti et al., 2015; Kumar et al., 2016; Manu et al., 2016; Sharma et al., 2021; Kaushal et al., 2024), but the India Model for Adaptive Comfort was built largely from office populations, and whether it describes manual workers sustaining 1.6 to 2.6 met in unconditioned premises is untested. Comfort response also varies with gender and role (Karjalainen, 2012; Indraganti and Humphreys, 2021), both of which differ systematically across this industry's tiers.

There is finally a regulatory vacuum. India's National Ambient Air Quality Standards (NAAQS) govern outdoor air, the Factories Act requires adequate ventilation without giving numbers, and no enforceable indoor standard reaches workplaces of the size dominating this cluster (Datta et al., 2017; Chithra and Shiva Nagendra, 2018), most cottage units falling below the employment threshold at which inspection applies at all. This study therefore set out to characterise the indoor environment of footwear units across three enterprise tiers through a full annual cycle, to test thermal comfort against both the Predicted Mean Vote model and the workers' own votes, to identify what governs air exchange in these buildings, and to establish how far each tier departs from ambient, health-based and occupational benchmarks.

2. Materials and methods

2.1 Study setting and enterprise tiers

Fieldwork took place in the leather footwear cluster of Agra, Uttar Pradesh, within the semi-arid composite climate zone of northern India. The city has a hot summer from April to June, a warm humid monsoon from July to September, a transitional post-monsoon period in October and November, and a cool winter from December to March, and it sits in an urban airshed carrying persistently high particulate loading (Kumari et al., 2020; Rahaman et al., 2021).

A frame of 42 operating units was stratified by workforce size following the Indian Micro, Small and Medium Enterprises classification into large industry (LI, above 200 employees, 6 units), small and medium enterprises (SME, 51 to 200 employees, 12 units) and cottage industry (CI, 5 to 50 employees, 24 units). Every unit relied on natural ventilation during production. Large premises were purpose-built halls with high ceilings, roof monitors and openable clerestory glazing, assisted by fans and sometimes evaporative coolers; SME premises were sheds with wall openings and ceiling fans; cottage units occupied converted residential rooms with typically one door and one window. No unit in any tier had local exhaust ventilation at the cementing station. Figure 1 shows the manufacturing sequence and the measurement stations, and Fig. S1 the full study design.

2.2 Sampling design and campaign

The design paired a physical measurement of the workstation environment with a right-here-right-now comfort ballot given to the worker occupying that station. Each pairing forms one record. Collection ran from 1 December 2023 to 13 December 2025 across 147 survey days, with one or two sessions per day scheduled to cover the morning and afternoon halves of the shift.

Of 426 workers approached, 378 records were retained after applying the ASHRAE 55 screening criteria of a complete record, a complete ballot, presence at the station for at least 30 minutes beforehand, and internal consistency. The retained records divide as LI 61, SME 108 and CI 209, and by season as 117 summer, 79 monsoon, 86 post-monsoon and 96 winter.

The unequal tier sizes follow from the sampling frame rather than from attrition. The frame held 6 large, 12 SME and 24 cottage units, a ratio of roughly 1:2:4 that mirrors the cluster itself, and effort was allocated in that proportion so the sample would resemble the population of establishments an inspector would actually meet. Cottage units also employ the largest share of the cluster workforce. The cost of this choice is that the cottage tier is characterised most precisely and the large tier least precisely, which Section 2.6 quantifies.

Instruments sat in the breathing zone, 1.1 to 1.5 m above the floor, roughly 0.5 m from the workstation and clear of direct fan discharge, logging across the session with the session mean used for analysis. Whether solvent-based pasting was active anywhere in the room was recorded as a binary attribute.

Outdoor air temperature and humidity were measured concurrently outside, and the published ambient air quality index recorded.

2.3 Instrumentation and derived variables

A multi-parameter monitor (Prana Air Cair+) measured air temperature, relative humidity, CO_2, TVOC, formaldehyde and particulate matter in three size fractions. Air velocity was measured with a vane anemometer (ACETEQ AM-101) and surface temperatures with an infrared thermometer (HTC MT4); Table S1 gives full details. All Cair+ channels log together, so a session's chemical and physical variables are strictly contemporaneous. Instruments were zeroed in outdoor air each morning and allowed ten minutes to stabilise before logging.

Three properties of this equipment govern what the measurements can carry. The monitor is a low-cost sensor package, factory-calibrated and not verified against a certified reference, with accuracy published for the temperature, humidity and CO_2 channels only. Electrochemical formaldehyde cells respond to other reduced organic species, including alcohols and aldehydes present in solvent-based adhesives, and the resulting bias is positive, so formaldehyde is reported throughout as apparent formaldehyde and read as an upper bound. A metal-oxide TVOC element responds to a mixture and yields a relative index of organic loading rather than a speciated result. Together these suit the instrument to the comparative question asked here, how tiers differ on identical equipment, and not to certifying absolute values. The tier contrasts are accordingly the firm result of this study and the absolute concentrations the softer one.

Mean radiant temperature was obtained from area-weighted enclosure surface temperatures rather than from a black globe as ISO 7726 specifies (ISO, 1998), because a globe needs fifteen to twenty minutes to equilibrate at each station and cannot be used on a moving production line. Area weighting smooths radiant asymmetry, so the radiant load from a single hot surface such as a midday roof sheet is likely understated. That bias is conservative here, since it works against the cottage units where the load is largest. Operative temperature was taken as the mean of air and mean radiant temperature, which is appropriate at these air speeds (ASHRAE, 2017):

$$T_{op} = \frac{T_a + T_r}{2}$$

TVOC was converted to mass units for comparison with mass-based guidelines using the molar volume of an ideal gas at 25°C and 101.3 kPa:

$$C_{mass} = C_{vol} \times \frac{M}{24.45}$$

The assumed molar mass matters, and its influence was tested rather than assumed. Across the solvents plausibly present in neoprene and polyurethane footwear adhesives the dataset mean of 2.01 ppm converts to between 4.61 mg m^{-3} on an isobutylene basis and 7.57 mg m^{-3} as toluene, a spread of a factor of 1.64 (Table S3). The conservative isobutylene basis is retained, mass equivalents are treated

as order-of-magnitude estimates carrying roughly plus 65 per cent uncertainty, and TVOC is reported in ppm wherever a mass comparison is not required. Speciation by sorbent sampling and chromatography would settle the question and is the clear next step.

2.4 Thermal comfort evaluation

Clothing insulation came from each worker's reported garment ensemble using the tables of ASHRAE 55 (2017). Metabolic rate was assigned from recorded primary activity following ISO 7730 (2005), at 1.2 met for seated light work, 1.4 for seated moderate work, 1.6 for standing light work, 2.0 for standing with walking and 2.6 for heavy manual work. Tabulated rates were used because instrumenting workers with calorimetry or heart-rate monitors during paid production was not permitted by employers or acceptable to workers, and because the same categories underpin the PMV model itself. The residual uncertainty is real, since an error of 0.2 met shifts PMV by about 0.2 scale units at these temperatures, but it is common to all three tiers and cannot generate the differences between them. Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) were computed from the six classical variables (Fanger, 1970; ISO, 2005), with PMV bounded at ± 3.5.

Thermal sensation was recorded on the seven-point ASHRAE scale from − 3 to + 3. Comfort temperature was estimated by the Griffiths method (Griffiths, 1990), which recovers an individual comfort temperature without requiring votes within a subgroup to span the neutral point:

$$T_c = T_{op} - \frac{TSV}{G}$$

with G = 0.33 K^{-1} for the main analysis and 0.25 and 0.50 K^{-1} for sensitivity. Griffiths was selected as the only estimator and regression of sensation on operative temperature was omitted. Favero et al. (2023) demonstrate failure of regression-based neutral temperatures in cases where the range of sampled temperatures is narrow compared to the range over which votes are cast, votes "saturate" at a scale endpoint, and the estimate requires extrapolation beyond the range of the data, with Favero et al. (2024) generalizing the argument to ordinal comfort data more broadly. All three of the conditions are satisfied here. The regression is only mentioned once, in 3.9, and used to demonstrate its size of error.

2.5 Ventilation assessment

Tracer decay was not possible in premises that are occupied continuously across the shift thus the evaluation of ventilation was made based on the steady state CO2 balance of ASTM D6245 (ASTM, 2018) which gives the ventilation rate per person based on the equilibrium indoor-outdoor CO2 difference and the metabolic generation rate of the occupants:

$$G = \frac{0.00276 \times \ A_{Du} \times \ M}{0.23\,RQ + 0.77}$$

$$V_o = \frac{G}{(C_{in} - C_{out}) \times \ 10^{-6}}$$

Here G is CO_2 generation per person (L s^{-1}), A_{Du} the DuBois surface area taken as 1.80 m^2, M the metabolic rate in met, RQ the respiratory quotient at 0.83, C_{in} the measured indoor concentration and C_{out} an assumed outdoor concentration of 415 ppm. Because M was assigned per worker, generation is workstation-specific rather than a population average.

Two limitations govern how this quantity is used. Equilibrium between generation and removal is a reasonable expectation in rooms of this size with stable occupancy and no mechanical supply, but the method overstates ventilation where occupancy has recently risen and understates it where occupancy has recently fallen, and no tracer measurement was available to check it. More importantly, the derived rate is computed from measured CO_2, so the two are linked by construction and any correlation between the rate and a pollutant that covaries with CO_2 is partly arithmetic. Derived ventilation rates are therefore used in this paper only as a descriptive indicator expressed in units comparable with a published benchmark. Wherever the relationship between dilution and pollutant concentration is examined, air velocity is used instead. Air velocity is measured directly, shares no term with CO_2 or with any pollutant, and is the quantity that physically separates these buildings.

2.6 Benchmarks and statistical treatment

India has no indoor air quality standard covering workplaces of this size, so concentrations were assessed against three independent benchmark families: the Indian NAAQS for $PM_{2.5}$ and PM_{10} (Central Pollution Control Board, CPCB, 2009); the WHO (2021) guidelines for the same pollutants together with the WHO indoor guideline of 0.1 mg m^{-3} for formaldehyde; and the American Conference of Governmental Industrial Hygienists (ACGIH, 2024) threshold limit value for formaldehyde of 0.1 ppm with its 0.3 ppm short-term limit. TVOC was compared with the 0.6 mg m^{-3} limit of GB/T 18883 (Standardization Administration of China, 2022) and the 3 mg m^{-3} upper band, CO_2 with 1000 ppm (Persily and Emmerich, 2012), ventilation with 10 L s^{-1} per person, and the thermal indices with ISO 7730 Category B. Compliance was expressed as the percentage of sessions exceeding each benchmark by tier. This was preferred to a modelled dose calculation because it needs nothing beyond a measured concentration and a published limit, carrying no assumption about inhalation rate, body weight, exposure duration or mixture composition. Its limitation is the converse: it establishes how often a limit was exceeded, not the size of any health effect.

Analyses used IBM SPSS Statistics 26 with α at 0.05, with the power simulation run in Python 3.11. Every environmental variable departed significantly from normality on both the Kolmogorov-Smirnov and Shapiro-Wilk tests, so non-parametric procedures were used throughout. Tiers and seasons were compared by Kruskal-Wallis H with Dunn post hoc tests and Bonferroni adjustment, sessions with and without pasting by Mann-Whitney U, and categorical responses by Pearson χ^2. Associations were quantified by Spearman rank correlation, and by Spearman partial correlation on ranks where a third variable could confound the interpretation. Effect sizes accompany every test: ε^2 for Kruskal-Wallis, $r = |z| / \sqrt{N}$ for each Dunn contrast (Table S4), the rank-biserial correlation for Mann-Whitney U, and Cramér's V for χ^2.

Because the tier sizes are unequal by design, the sensitivity of the Kruskal-Wallis test under the realised allocation was established by simulation rather than assumed. Four thousand datasets were drawn at each of a range of effect sizes, sampling 61, 108 and 209 observations from normal distributions separated by a fixed increment per tier step. The test reaches 80% power at about 0.22 standard deviations per step and exceeds 97% at 0.30. On that scale the observed effects are 1.29 SD for air velocity, 1.10 for apparent formaldehyde, 1.05 for CO_2, 0.99 for TVOC and 0.65 for $PM_{2.5}$, all comfortably detectable, while air temperature at 0.24 SD sits near the limit and is interpreted more cautiously. A two-group comparison involving the smallest tier alone reaches 86% power at a 0.5 SD difference.

3. Results and discussion

3.1 The sampled population

Workers were young, averaging 28.6 ± 8.8 years across a range of 18 to 62, and predominantly male, though the balance shifted by tier, half the large-unit respondents being women against 20.4% in SME and 16.7% in cottage premises. Mean tenure in the industry was 5.57 ± 3.44 years against 2.96 ± 2.56 in the current unit, indicating considerable movement between establishments. Three characteristics run against enterprise size and compound the exposure gradient below: shift length rose from 8.50 to 9.05 to 10.30 h, reaching 13 h in individual cases; clothing insulation fell from 0.85 to 0.70 to 0.58 clo, consistent with adaptive divestment in warmer rooms; and metabolic rate rose from 1.60 to 1.82 met with the larger share of manual lasting where mechanisation is absent. Table S2 gives full detail.

3.2 The indoor environment across enterprise tiers

Table 1 reports every measured parameter by tier and Fig. 2 shows the distributions. Medians and interquartile ranges appear in Table S3, and the complete set of pairwise contrasts with effect sizes in Table S4.

Table 1
Measured environmental, comfort and ventilation parameters by enterprise tier, with the Kruskal-Wallis test of the tier effect

Parameter	LI (*n* = 61)	SME (*n* = 108)	CI (*n* = 209)	All (*n* = 378)	Range	Tier effect
Air temperature, T_a (°C)	29.39 ± 7.50	29.92 ± 7.72	33.03 ± 7.42	31.55 ± 7.68	12.70 to 47.95	H = 16.94, p < 0.001, ε^2 = 0.040
Mean radiant temperature, T_r (°C)	29.81 ± 7.65	30.81 ± 8.13	34.94 ± 8.25	32.93 ± 8.41	12.90 to 50.85	H = 26.95, p < 0.001, ε^2 = 0.067
Operative temperature, T_{op} (°C)	29.60 ± 7.57	30.36 ± 7.92	33.98 ± 7.83	32.24 ± 8.03	12.80 to 49.40	H = 21.63, p < 0.001, ε^2 = 0.052
Relative humidity (%)	42.00 ± 16.60	52.15 ± 14.54	57.20 ± 16.78	53.31 ± 16.99	17.60 to 91.90	H = 33.50, p < 0.001, ε^2 = 0.084
Air velocity, v_a (m s^{-1})	0.80 ± 0.17	0.40 ± 0.09	0.16 ± 0.05	0.33 ± 0.25	0.07 to 1.10	H = 297.61, p < 0.001, ε^2 = 0.788
CO_2 (ppm)	709.25 ± 63.29	909.83 ± 109.51	1359.91 ± 188.24	1126.31 ± 308.89	615.70 to 1724.70	H = 288.31, p < 0.001, ε^2 = 0.763
TVOC (ppm)	0.71 ± 0.36	1.55 ± 0.56	2.62 ± 0.72	2.01 ± 0.97	0.21 to 4.29	H = 228.57, p < 0.001, ε^2 = 0.604
Apparent formaldehyde (ppm)	0.10 ± 0.03	0.18 ± 0.03	0.29 ± 0.06	0.23 ± 0.09	0.05 to 0.41	H = 281.61, p < 0.001, ε^2 = 0.746
PM_1 (μg m^{-3})	38.15 ± 13.89	63.17 ± 25.66	75.38 ± 27.46	65.88 ± 28.46	17.30 to 137.70	H = 95.97, p < 0.001, ε^2 = 0.251
$PM_{2.5}$ (μg m^{-3})	62.64 ± 23.44	102.48 ± 41.29	121.38 ± 43.29	106.50 ± 45.21	29.30 to 219.80	H = 90.51, p < 0.001, ε^2 = 0.236
PM_{10} (μg m^{-3})	79.07 ± 29.75	129.17 ± 51.93	151.53 ± 54.84	133.45 ± 56.83	37.10 to 271.30	H = 85.13, p < 0.001, ε^2 = 0.222

Values are mean ± standard deviation. All variables depart significantly from normality, so medians and interquartile ranges are given in Table S3 and all inference is non-parametric. Pairwise Dunn contrasts with effect sizes appear in Table S4.

Parameter	LI (*n* = 61)	SME (*n* = 108)	CI (*n* = 209)	All (*n* = 378)	Range	Tier effect
PMV	1.58 ± 1.67	1.86 ± 1.56	2.50 ± 1.33	2.17 ± 1.50	−3.50 to + 3.50	$H = 27.85$, $p < 0.001$, $\varepsilon^2 = 0.069$
PPD (%)	64.00 ± 35.95	66.64 ± 37.04	78.32 ± 32.97	72.67 ± 35.14	5.00 to 100.00	$H = 22.81$, $p < 0.001$, $\varepsilon^2 = 0.055$
Ventilation rate (L s^{-1} per person)	29.09 ± 7.82	19.79 ± 7.14	10.40 ± 3.52	16.10 ± 8.96	4.78 to 48.83	$H = 232.82$, $p < 0.001$, $\varepsilon^2 = 0.616$
Outdoor air temperature (°C)	29.69 ± 7.56	28.49 ± 7.71	29.71 ± 7.20	29.36 ± 7.41	12.00 to 43.30	$H = 2.04$, $p = 0.360$, $\varepsilon^2 = 0.000$
Outdoor relative humidity (%)	49.11 ± 16.47	52.44 ± 14.93	52.55 ± 16.49	51.96 ± 16.06	18.00 to 82.00	$H = 1.68$, $p = 0.431$, $\varepsilon^2 = 0.000$
Outdoor air quality index	209.08 ± 69.82	227.61 ± 84.45	200.88 ± 79.97	209.84 ± 80.39	69.00 to 413.00	$H = 7.74$, $p = 0.021$, $\varepsilon^2 = 0.015$

Values are mean ± standard deviation. All variables depart significantly from normality, so medians and interquartile ranges are given in Table S3 and all inference is non-parametric. Pairwise Dunn contrasts with effect sizes appear in Table S4.

Mean indoor air temperature was 31.55 ± 7.68°C, ranging from 12.70°C on a winter morning to 47.95°C in a cottage unit at the height of summer. Cottage premises were significantly warmer than either other tier at 33.03°C, against 29.92°C in SME and 29.39°C in large units ($H = 16.94$, $p < 0.001$, $\varepsilon^2 = 0.040$), with the large-SME contrast not significant, and temperature exceeded 30°C in 59.5% of sessions. Mean radiant temperature exceeded air temperature by 1.38 K on average, the excess widening from 0.42 K in large units to 1.91 K in cottage rooms. This is what an uninsulated envelope looks like from the inside. The workers, prompted by no question, spoke about the effect of solar gain on the roof surface, and how this re-radiates heat to the areas below the roof. “The roof sheet becomes very hot after midday and the whole hall heats up” was one of the most frequently occurring free text observations. Roshan et al. (2017) and Sakhri et al. (2022) determine the same radiant term to be controlling in hot dry environments, the term that a ceiling fan cannot touch.

Relative humidity averaged 53.31 ± 16.99% and rose as unit size fell, from 42.0% to 52.2% to 57.2% ($H = 33.50$, $p < 0.001$), all three contrasts significant, though only 26.2% of sessions lay outside the 30 to 70% band. The higher humidity measured indoors in smaller rooms is due to moisture generated by occupants of the space that is retained in an area with poor indoor air ventilation (Wolkoff, 2018).

CO2 followed the same ordering, rising from 709 ± 63 to 910 ± 110 to 1360 ± 188 ppm ($H = 288.31$, $p < 0.001$, $\varepsilon^2 = 0.763$), crossing 1000 ppm in 98.6% of cottage sessions and none in the large tier. CO2 is not

dangerous at these concentrations, but it is a marker to indicate the level of dilution achieved and what comes next.

The Kruskal-Wallis test and all three Dunn contrasts were significant for each chemical pollutant, and all of them increased monotonically from the large to the cottage units. TVOC averaged 2.01 ± 0.97 ppm overall, rising from 0.71 ± 0.36 through 1.55 ± 0.56 to 2.62 ± 0.72 ppm (H = 228.57, ε² = 0.604). The overall mean is approximately 4.6 mg m − 3 on the isobutylene basis, which is compared to an eight-hour indoor limit of 0.6 mg m − 3 and with the upper band of 3 mg m − 3. These concentrations are not uncommon when solvent adhesives are used without extraction, but the continued exposure throughout a shift is what makes this exposure different from the episodically higher concentrations found in homes and institutions (Feng et al., 2023; Vornanen-Winqvist et al., 2020).

The more worrisome of the two is apparent formaldehyde. Bearing in mind that these are sensor-equivalent values bounding the truth from above, the mean of 0.225 ± 0.088 ppm rose from 0.095 to 0.177 to 0.288 ppm across the tiers (H = 281.61, ε² = 0.746), reaching 0.415 ppm at maximum. For a small pasting room, Qin et al. (2020) reported similar loadings within the coach cabins and blamed them on the adhesives and interior finishes. Particulate concentrations were high everywhere: PM2.5 averaged 106.5 ± 45.2 µg m − 3 and PM10 133.4 ± 56.8 µg m − 3, both rising as premises shrank (PM2.5: 62.6, 102.5 and 121.4 µg m − 3; H = 90.51, p < 0.001). There was nearly perfect collinearity between the three fractions with ρ ≥ 0.98, and this PM1/PM2.5 ratio indicates a prevalence of fine fraction, as opposed to coarse dust, which is primarily attributed to combustion-based urban background and abrasion products, not just to coarse dust (Bousiotis et al., 2023; Roy et al., 2024).

Two features deserve emphasis. The gradient is steeper for what is emitted indoors, TVOC rising 3.7-fold and formaldehyde 3.0-fold against 1.9-fold for $PM_{2.5}$, as expected if smaller premises differ chiefly in their capacity to remove an internal load. And grouping sessions by workstation type, whether cementing, cutting, stitching, lasting or finishing, produced no significant difference in TVOC, formaldehyde or $PM_{2.5}$ ($p > 0.05$ throughout). Exposure here is a property of the room, not the bench: solvent vapour released at the pasting table disperses through an undivided volume and reaches workers who never handle adhesive, so protection issued only to applicators would leave most of the exposed workforce uncovered.

3.3 The pasting operation as the dominant indoor source

Sessions with pasting active (n = 293) were compared with those without (n = 85) in Fig. S4. TVOC was 2.14 times higher when adhesive was being applied, at 2.28 against 1.06 ppm (U = 21473, $p < 0.001$, r_{rb} = − 0.72), an effect size that settles the question of the dominant source. Apparent formaldehyde was 1.20 times higher (0.234 against 0.196 ppm), $PM_{2.5}$ 1.17 times higher (110.0 against 94.3 µg m^{-3}) and CO_2 1.15 times higher, all at $p < 0.001$.

That formaldehyde rises less steeply than TVOC points to two partly separate sources. Solvent flash-off produces a large, sharply varying VOC signal, while formaldehyde carries an additional steady

component, plausibly from leather finishes, board and resin-bonded parts stored in the same room, that persists when no adhesive is in use. The accompanying rise in CO_2 and, as Section 3.4 shows, fall in air velocity reveal a compounding behavioural effect: cementing is concentrated in the busiest periods, when occupancy peaks and doors are more often closed so that dust does not settle on freshly glued surfaces.

3.4 Air movement, ventilation and their drivers

Air velocity is treated as the primary ventilation indicator for the reason given in Section 2.5. It fell from 0.80 ± 0.17 m s^{-1} in large units to 0.40 ± 0.09 in SME and 0.16 ± 0.05 in cottage premises, an effect accounting for 79% of the variance ($\varepsilon^2 = 0.788$) and the largest of any variable measured (Fig. 3a).

Air velocity correlated negatively with every internally generated pollutant: TVOC at $\rho = -0.714$, apparent formaldehyde at $\rho = -0.736$ and CO_2 at $\rho = -0.782$, all at $p < 0.001$. Because CO_2 is itself a dilution marker, the possibility that these merely restate a shared dependence on occupancy was tested by partial correlation. Holding CO_2 constant, air velocity retains an independent negative association with TVOC ($r = -0.391$, $p < 0.001$) and with apparent formaldehyde ($r = -0.392$, $p < 0.001$), while its association with $PM_{2.5}$ collapses to non-significance ($r = -0.051$, $p = 0.326$). That asymmetry is what physical reasoning predicts and not what an arithmetic artefact would produce, since air movement removes the two gases generated indoors and does not remove the particulate fraction largely infiltrated from outside.

Derived ventilation rates, a descriptive indicator only, averaged 16.10 ± 8.96 L s^{-1} per person and ordered the tiers at 29.09 ± 7.82, 19.79 ± 7.14 and 10.40 ± 3.52 (Fig. 3b). Against the 10 L s^{-1} per person benchmark no large-unit session and only 0.9% of SME sessions fell short, whereas 52.2% of cottage sessions did. Figure 3c shows that each tier is located on the theoretical mass-balance curve, with large units on the flat limb of the curve, where additional airflow provides relatively small additional reductions, and cottage units on the steep limb of the curve, where small increases in the rate of air exchange would result in larger reductions for each internally generated pollutant.

Here, air flows according to something other than weather. Neither outdoor air temperature ($\rho = -0.076$, $p = 0.142$) nor outdoor humidity ($\rho = -0.025$, $p = 0.629$) was meaningfully associated with indoor air velocity, and within each tier seasonal variation was negligible: 0.73 to 0.85 m s − 1 in large units ($p = 0.63$), 0.36 to 0.43 in SME premises ($p = 0.112$) and 0.14 to 0.17 in cottage units, where significance ($p = 0.014$) spans a practically meaningless 0.03 m s − 1. There was no seasonality in Derived ventilation rate ($p = 0.052$). The amount of temperature change outdoors affects the opening of these buildings only slightly if at all.A change in temperature of 26 K outside, does not change the operation of the buildings in any substantial way.

There are two mechanisms for this. The openings are fixed in place instead of opened by action and not operated, for a cottage unit has one door and one window, both of which were open during the production for light and access, and nothing to be opened when the weather changes. Where there is any

discretion, it is for production, not for climate: air velocity was much lower during pasting sessions than without pasting (0.300 m s − 1 compared to 0.432 m s − 1 ($p < 0.001$), respectively). Actually, air velocity and derived ventilation rate were found to be strongly correlated ($\rho = 0.695$), which means they were both from the same openings that entail fan assistance. That coupling is the main design challenge as air movement is the workers' most important thermal resource, with 85.4% requesting more air movement, but in cottage units, the openings through which this air movement could occur are limited in number and are intentionally plugged when they are most needed.

3.5 Outdoor influence and seasonality

Indoor-to-outdoor ratios for the directly measured variables show large units running very nearly thermally neutral with respect to the street, at a ratio of 0.99, against 1.06 in SME and 1.12 in cottage premises, corresponding to mean differences of − 0.30, + 1.43 and + 3.32 K. Since internal gains from machinery are lowest in the cottage tier, that excess must come from solar gain through a poorly insulated envelope combined with restricted air exchange, the same combination behind the radiant temperatures of Section 3.2. Humidity ratios ordered identically at 0.84, 1.00 and 1.10, with indoor air drier than outdoor only in the large units.

Outdoor concentrations of CO_2, TVOC, formaldehyde and particulate matter were not measured, so no ratio is reported for them. The relationship worth stating is the direct one: indoor $PM_{2.5}$ correlated strongly with the published ambient air quality index ($\rho = 0.769$, $p < 0.001$). As the index is an ordinal composite, this rank correlation needs no conversion and establishes that much of the indoor particulate burden follows the outdoor airshed. Ratios against an outdoor concentration recovered by inverting the CPCB sub-index breakpoints appear in Table S5 rather than here, since the index is the maximum across sub-indices and the inversion is piecewise linear across bands up to 130 μg m^{-3} wide, giving at least 30 to 50% uncertainty before any ratio is formed. Nothing here rests on them. The evidence for an indoor contribution is instead the tier gradient in measured $PM_{2.5}$, from 62.6 to 121.4 μg m^{-3}, against an outdoor index barely differing between tiers ($\varepsilon^2 = 0.015$). Abrasion and resuspension are the plausible additions (Maestas et al., 2019; Bousiotis et al., 2023).

Season shaped the thermal variables and particulate matter but not the solvent-related pollutants (Fig. S2). Indoor temperature fell from 38.28°C in summer to 22.12°C in winter ($H = 250.31$, $p < 0.001$) and PPD followed from 96.3% to 29.9%. $PM_{2.5}$ moved the other way, from 68.7 μg m^{-3} in the monsoon to 154.8 in winter, a factor of 2.25 carrying the familiar signature of the northern Indian winter, when a shallow boundary layer, weak wind and regional biomass burning raise ambient loading (Kumari et al., 2020; Rahaman et al., 2021). TVOC and formaldehyde showed no seasonal variation ($p = 0.174$ and 0.077), so emission is set by production volume rather than weather: solvent control must operate year-round while particulate control has a clear winter priority.

3.6 Thermal comfort

PMV averaged 2.17 ± 1.50 and exceeded ± 0.5 in 91.3% of observations, with a mean PPD of 72.7%. By tier it rose from 1.58 to 1.86 to 2.50 (H = 27.85, p < 0.001). On the model's own terms these workplaces are thermally unacceptable for most of the working year.

The workers' votes tell a related but milder story (Fig. 4). Mean thermal sensation vote was 1.54 against a mean PMV of 2.17, a bias of + 0.63 ± 0.81 scale units that was highly significant (Wilcoxon, p < 0.001) despite a strong monotonic association between the two (ρ = 0.795). PMV therefore ranks conditions correctly but overstates their severity, and the gap widens as conditions warm, as Fig. 4b shows through a regression lying below the identity line across the whole warm range. This is the adaptive gap documented repeatedly in warm-climate field studies (Indraganti et al., 2015; Manu et al., 2016; Kumar et al., 2016; Rijal et al., 2019; Sharma et al., 2021), and it appears here in a population for which it had not been quantified, namely manual workers sustaining 1.6 to 2.6 met in unconditioned premises. The dissatisfaction figures agree, PPD predicting 72.7% against 59.8% actually rating conditions unacceptable, an overprediction of about 13 percentage points that matches what Kaushal et al. (2024) report for naturally ventilated Indian buildings.

The Griffiths comfort temperature is 27.58 ± 5.59°C at G = 0.33 K^{-1}, bounded by 26.09 and 29.17°C across the sensitivity range, exceeding the ISO 7730 Category B upper limit at every value tested. It tracked season, rising from 21.83°C in winter through 25.99 post-monsoon and 29.03 in the monsoon to 32.51°C in summer. A swing of 10.7 K is large but not anomalous for a population continuously exposed to the outdoor climate with wide latitude in clothing, and it confirms that a fixed setpoint would be the wrong design target here. Comfort temperature differed less between tiers, at 26.08, 26.49 and 28.59°C, than measured temperature did, indicating partial adaptation. It was incomplete, however: the gap between cottage comfort temperature and the cottage mean operative temperature of 33.98°C is 5.4 K against 3.5 K in large units. Workers in the smallest premises have adjusted their expectations upward and still fall further short.

3.7 Occupant perception and reported symptoms

Subjective assessments separated the tiers even more sharply than the measurements (Fig. 5). Mean satisfaction with the thermal environment fell from + 0.23 in large units to − 0.77 in SME and − 2.14 in cottage premises on a seven-point scale (H = 157.99, p < 0.001, ε^2 = 0.416; Cramér's V = 0.497). Ventilation was rated poor or very poor by 8.2%, 25.9% and 66.0% of respondents respectively (V = 0.438). Perceived air movement showed the largest categorical effect of all (V = 0.606), with 127 of 378 workers describing the air at their station as still, most of them in cottage rooms.

Thermal acceptability was low everywhere and was the one perception variable not differing significantly across tiers (χ^2 = 15.12, p = 0.057). Only 26.7% of workers found conditions acceptable or better, at 32.8%, 35.2% and 20.6% by tier, so that a third of workers even in the best-provided premises found conditions unacceptable. Preferences ran one way: 79.9% wanted a cooler environment and 85.4% more air movement. Access to control was stratified along the same axis, with evaporative cooling reaching 73.8% of large-unit workers against 3.8% in cottage premises and air conditioning 23.0% against 1.0%,

while 22 workers, almost all in cottage rooms, reported that breaks were not permitted at all. Since behavioural adaptation is the main route by which occupants of naturally ventilated buildings stay comfortable (Brager et al., 2015; Rijal et al., 2019), the concentration of the worst environments and the fewest adaptive options in the same tier is the central inequity this study reveals.

Workers were also asked whether they attributed any of a list of symptoms to their working environment. The instrument was assembled around the ASHRAE 55 ballot with symptom items drawn from the occupational literature; it is not a validated clinical questionnaire, it records attribution and presence rather than duration or severity, and it was surveyor-administered. The results are therefore what workers report, not diagnosed morbidity, and the full ballot is provided as File S6. At least one symptom was reported by 86.5% of respondents. Excessive sweating was commonest at 58.2%, followed by fatigue at 47.6% and headache at 46.0%, with breathing difficulty at 19.0%, dizziness at 14.8%, muscle cramps at 13.8%, nausea at 10.6% and skin rash at 9.8%. Every symptom differed significantly across tiers (χ^2, $p < 0.05$ in all eight cases), and the contrasts were large: headache rose from 19.7% in large units to 62.7% in cottage premises, breathing difficulty from 4.9% to 26.8% and excessive sweating from 18.0% to 79.9%.

Reporting also varied with the pasting operation. Workers surveyed during active pasting reported headache more often, at 49.8% against 32.9% ($p = 0.009$), and breathing difficulty far more often, at 22.2% against 8.2% ($p = 0.006$), while symptoms without a plausible solvent aetiology, namely cramps, rash and dizziness, showed no significant association. A difference this selective is harder to explain by generalised over-reporting than by exposure, but it is not evidence of an exposure-response relationship in the epidemiological sense and none is claimed, the design being cross-sectional with symptom status and exposure recorded in the same encounter. Just over half the workforce, 51.9%, said the smell of adhesive worsened their discomfort.

Three checks bear on how far these reports can be trusted. Interviewer effects across the five surveyors were not significant for sensation vote ($H = 9.22$, $p = 0.056$) or symptom count ($H = 6.97$, $p = 0.138$), and time of day showed no significant association with any environmental or comfort variable. The third check is less comfortable: workers reporting at least one symptom had significantly shorter tenure than those reporting none, at 5.28 against 7.45 years ($p < 0.001$), the reverse of what cumulative exposure predicts. Either a healthy-worker survivor effect or habituation would produce this, and the data cannot separate them, but on either reading the prevalences reported here understate the burden among workers who have already left.

Satisfaction is also an incomplete guide to exposure, correlating with air velocity ($\rho = 0.59$), apparent formaldehyde ($\rho = -0.56$), CO_2 ($\rho = -0.54$) and ventilation rate ($\rho = 0.46$), but not at all with particulate matter ($\rho = 0.02$). Workers evidently perceive stagnant, odorous air and weigh it in their judgement, while fine particulate matter, which failed its WHO guideline in every session measured, stays invisible to them. Williams et al. (2024) report the same asymmetry domestically (Fig. S3). Worker complaint cannot

therefore serve as surveillance for particulate exposure, and monitoring in this sector must include instrumental measurement of PM.

3.8 Compliance with reference and occupational limits

Table 2 gives the proportion of sessions exceeding each benchmark, and three points follow from it.

Table 2
Percentage of monitoring sessions exceeding each reference value, by enterprise tier

Criterion	LI	SME	CI	All
CO_2 > 1000 ppm (inadequate outdoor air supply)	0.0	22.2	98.6	60.8
CO_2 > 1500 ppm	0.0	0.0	28.7	15.9
$PM_{2.5}$ > 60 µg m^{-3} (NAAQS 24 h, India)	49.2	73.1	100.0	84.1
$PM_{2.5}$ > 15 µg m^{-3} (WHO 2021 24 h)	100.0	100.0	100.0	100.0
PM_{10} > 100 µg m^{-3} (NAAQS 24 h, India)	26.2	66.7	81.3	68.3
PM_{10} > 45 µg m^{-3} (WHO 2021 24 h)	86.9	100.0	100.0	97.9
Apparent formaldehyde > 0.08 ppm (WHO indoor guideline)	63.9	100.0	100.0	94.2
TVOC > 0.6 mg m^{-3} (GB/T 18883)	95.1	100.0	100.0	99.2
TVOC > 3 mg m^{-3} (upper acceptability band)	4.9	66.7	96.7	73.3
T_a outside 23 to 30°C	72.1	73.1	76.6	74.9
T_a > 30°C	49.2	50.9	67.0	59.5
RH outside 30 to 70%	31.1	17.6	29.2	26.2
|PMV| > 0.5 (ISO 7730 Cat. B)	86.9	88.0	94.3	91.3
|PMV| > 0.7 (ISO 7730 Cat. C)	83.6	85.2	90.9	88.1
PPD > 10% (ISO 7730 Cat. B)	86.9	88.0	94.3	91.3
Ventilation rate < 10 L s^{-1} per person	0.0	0.9	52.2	29.1
Ventilation rate < 5 L s^{-1} per person	0.0	0.0	1.0	0.5

Apparent formaldehyde is the priority contaminant, and the case rests on no modelling assumption. Concentrations exceeded the ACGIH eight-hour threshold limit value of 0.1 ppm in 91.3% of all sessions

and in every session in the SME and cottage tiers, with 45.9% of large-unit sessions also in exceedance, and the 0.3 ppm short-term limit was exceeded in 43.5% of cottage sessions. Occupational limits are set for healthy adults on a working-lifetime basis and are far more permissive than public-health guidance, so breaching them by direct measurement is the graver finding, though the WHO indoor guideline was itself exceeded in 94.2% of sessions. Formaldehyde is a confirmed human carcinogen and a respiratory and dermal sensitiser, which places these concentrations beyond what a comfort-oriented framing can accommodate. The sensor caveat of Section 2.3 applies, but a bias large enough to bring every SME and cottage session below the limit is implausible.

Particulate exposure is uniformly poor and largely independent of tier. Not one session met the WHO 24-hour $PM_{2.5}$ guideline of 15 µg m^{-3}, and 97.9% failed the 45 µg m^{-3} PM_{10} guideline. Against the more permissive Indian standards, 84.1% exceeded 60 µg m^{-3} for $PM_{2.5}$ and 68.3% exceeded 100 µg m^{-3} for PM_{10}. The tier gradient is present but shallow, for the reason given in Section 3.5, so improving ventilation will not resolve it and may worsen it in winter. Particulate control here requires filtration or source capture rather than dilution.

TVOC, CO_2 and the thermal indices separate the tiers sharply. The 0.6 mg m^{-3} TVOC limit was breached in 99.2% of sessions and the 3 mg m^{-3} band in 73.3%, the latter rising from 4.9% of large-unit sessions to 96.7% of cottage sessions, while CO_2 exceeded 1000 ppm in 98.6% of cottage sessions and none in the largest tier, and ISO 7730 Category B was breached in 91.3% of sessions overall. Read together the benchmark families converge on one division: what is generated indoors tracks enterprise tier and is governed by dilution, while particulate matter is high everywhere and is governed by the ambient environment. Two caveats attach. Compliance percentages describe how often a limit was exceeded rather than by how much, and long-term exposure to volatile organic compounds and fine particles carries respiratory and cardiovascular consequences (Wolkoff, 2018; Supasri et al., 2023) that no compliance statistic captures.

3.9 Implications and limitations

Enterprise size is the organising variable for occupational exposure in this cluster, and it acts almost entirely through ventilation. The same process, materials and outdoor climate produce a 3.7-fold difference in TVOC and a 3.0-fold difference in apparent formaldehyde, and move the proportion of sessions with inadequate outdoor air supply from none to almost all, according to nothing beyond the size of the establishment. The units at the wrong end of that gradient are precisely those falling outside the scope of factory inspection.

The intervention hierarchy that follows matches what the workers proposed. Of the 234 offering a suggestion, cross-ventilation and evaporative cooling in the production area rather than only the office were each named by 14.5%, more windows by 11.5%, and exhaust fans in the pasting section by 10.3%. Local exhaust ventilation at the cementing station addresses the dominant source directly and is the single highest-value measure, yet it was absent from every unit studied. General ventilation improvement

would shift cottage units on the steep limb of the mass-balance relationship, thus reducing all of the pollutants that are generated in the units at once; water-based adhesive would attack the problem at the source; and roof insulation would address the radiant load which fans cannot reach. Respiratory protection will be the final option, and if worn, it must be covering the entire room and not the applicators.

There are a number of restrictions in three categories. On measurement, it's a low cost sensor package, factory calibrated, with no independent verification, whose accuracy is not provided for the particulate, formaldehyde and TVOC channels; the formaldehyde cell is cross sensitive with a positive bias; TVOC mass equivalent varies by 1.64 depending on the solvent; the mean radiant temperature is based on an infrared surface measurement, not a globe; and the outdoor levels were not measured simultaneously with the indoor levels. Each of these bears more heavily on absolute values than on the tier comparisons, which used identical equipment under one protocol throughout.

On uncontrolled variables, room volume and occupant density were not recorded, so ventilation could not be expressed as an air change rate and crowding cannot be separated from air exchange in the CO_2 gradient, while building age, envelope construction and machinery age were not catalogued although all three vary within tiers. What could be tested was: time of day showed no significant association with any variable and its distribution did not differ significantly across tiers ($\chi^2 = 5.52$, $p = 0.063$), and surveyor identity showed none with sensation vote or symptom count. Outdoor wind speed was not recorded, though since outdoor temperature has no detectable influence on indoor air velocity here it is unlikely to change the conclusion.

On inference, health outcomes are self-reported, cross-sectional and collected with an unvalidated instrument, so no causal claim is made, and the inverse tenure association suggests a survivor or habituation effect this design cannot resolve. As an illustration of the estimation problem set out in Section 2.4, ordinary least squares regression of sensation on operative temperature gives TSV = $0.1217 \cdot T_{op} - 2.3866$ ($r = 0.783$, $R^2 = 0.613$), implying a neutral temperature of 19.6°C, roughly eight kelvin below the Griffiths estimate and below any temperature at which this population reported comfort. That discrepancy follows directly from scale saturation and extrapolation beyond the sampled range, and it is reported as a caution rather than a result. Finally, this is one cluster in one city: the mechanisms are general, the concentrations need not transfer.

4. Conclusions

In the Agra footwear cluster, size of the enterprise determined exposure, in this case by means of ventilation; across 378 paired measurements and ballots taken on 147 days and four seasons. All pairwise comparisons between the units were significant, with every pollutant increasing monotonically from large to cottage units, and air velocity decreasing monotonically from 0.80 to 0.16 m s − 1, accounting for 79% of its variance. To determine if air movement is a confounding factor, it was tested

for partial correlation with TVOC and apparent formaldehyde with the CO2 level held constant, and air movement remains associated with the other two variables independently of CO2.

Formaldehyde is the priority contaminant with 91.3% of all sessions exceeding the ACGIH 8-hour TLV, and all sessions in the SME and cottage tiers exceeding the ACGIH 8-hour TLV, and 43.5% of cottage sessions exceeding the short-term TLV. Particulate exposure is poor everywhere, and is not mainly related to enterprise size; no session exceeded the guideline of the WHO for PM2.5, and exposure in the home was closely correlated with ambient exposure, meaning that dilution alone will do little to control particulate exposure.

Solvent based pasting is the most common indoor source, increasing the concentration of TVOC by 2.14-fold, but as in other sources, it is a room characteristic, and controls directed at the applicator would leave most workers unprotected. Air changes in these buildings are dictated by production, not weather: there was no association between outdoor temperature and indoor air velocity across the 26 K seasonal range; and air velocity dropped significantly where adhesive was applied.

Thermal conditions did not meet ISO 7730 Category B requirements for 91.3% of observations, and the PMV model overestimated the scale of their failure by 0.63 scale units, and their overprediction of dissatisfaction by 13 percentage points. The Griffiths comfort temperature of 27.58 ± 5.59°C confirms substantial adaptation, and a residual 5.4 K gap in cottage units shows it to be incomplete. Environmental burden and adaptive capacity are inversely distributed: the workers facing the highest temperatures, concentrations and shift lengths have the least access to cooling, fan control and rest breaks.

The least regulated establishments carry the greatest burden, and the single most effective control, local exhaust ventilation at the cementing station, was absent from every unit studied. India has no enforceable indoor air quality standard for workplaces of this scale. The concentrations reported here, measured against ambient standards, international guidelines and occupational limits alike, indicate that such a standard is needed and that it must be framed with the technical and financial realities of small enterprises in mind if it is to reach the workers who need it most.

Declarations

Ethics Declaration The study was conducted in accordance with the applicable ethical standards and institutional requirements. Ethical approval was obtained from the relevant institutional ethics committee prior to commencement of the study.

Consent to Participate Informed consent was obtained from all participants involved in the study prior to their participation. The participants were informed about the purpose and nature of the study, and their participation was voluntary.

Competing interests The authors declare that they have no competing interests, whether financial or non-financial, that are directly or indirectly related to the work submitted for publication.

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Clinical trial number Not applicable.

Data availability The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request. Data may be made available subject to appropriate institutional, ethical, and confidentiality requirements.

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Figures

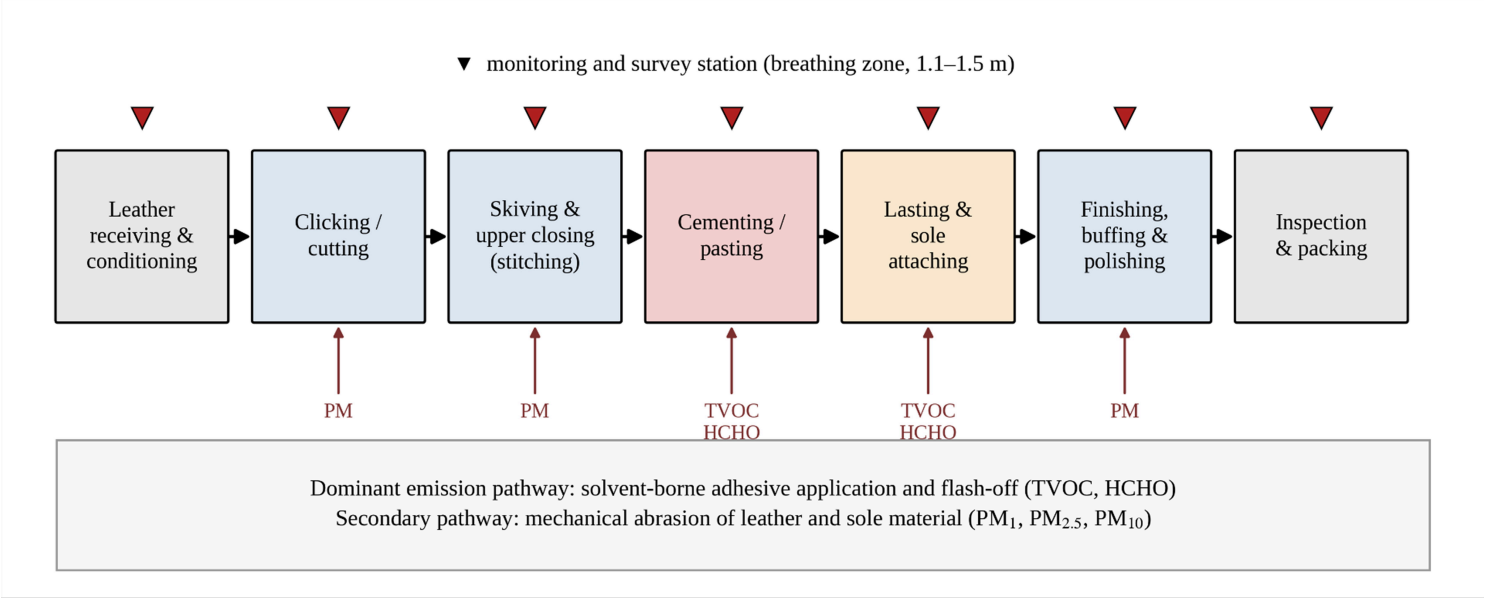


Figure 1

Footwear manufacturing sequence, dominant emission pathways and the location of the combined monitoring and survey stations.

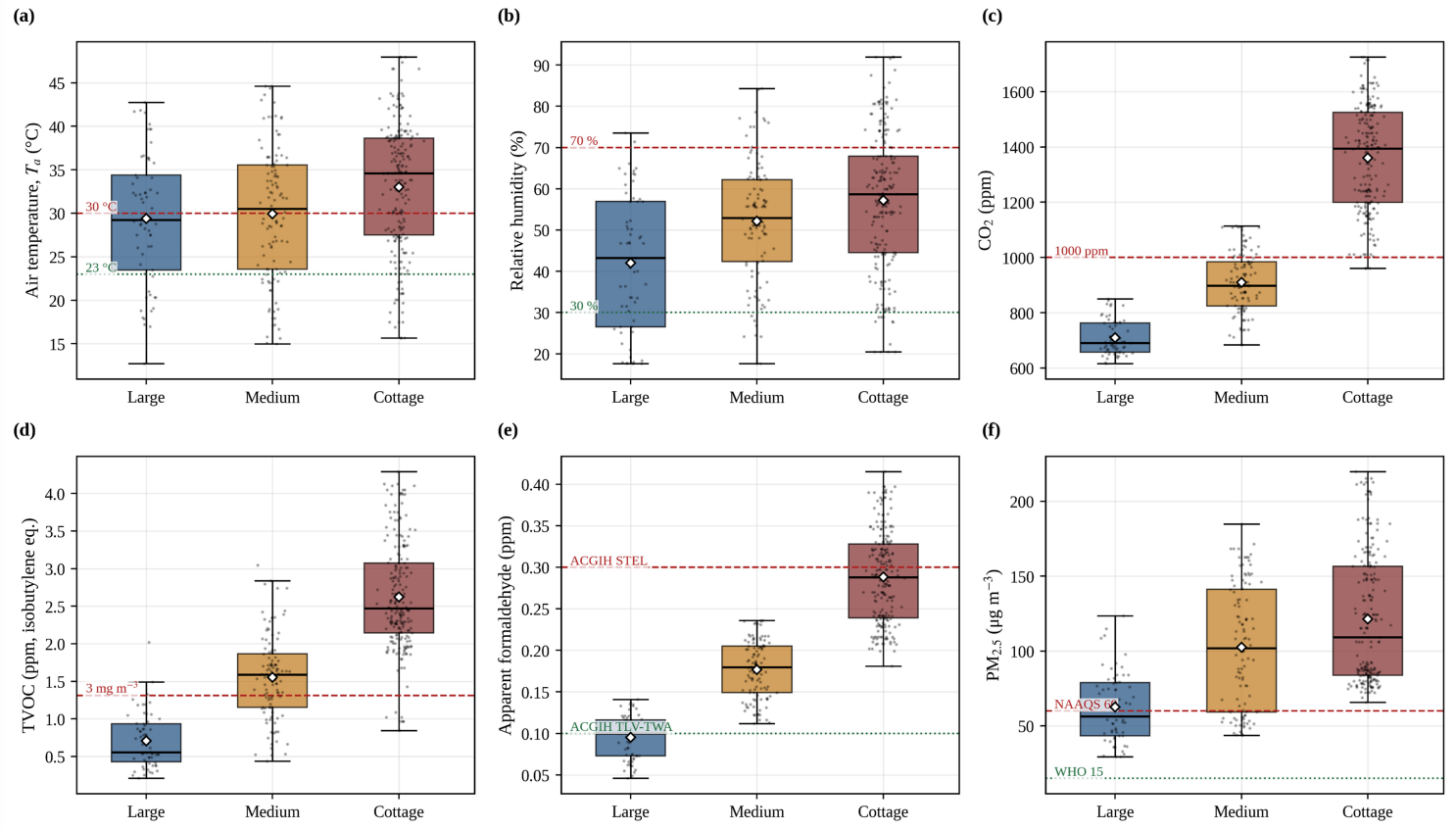


Figure 2

Indoor environment by enterprise tier: (a) air temperature, (b) relative humidity, (c) CO_2, (d) TVOC, (e) apparent formaldehyde and (f) $PM_{2.5}$. Boxes span the interquartile range, the line is the median, the open diamond the mean, and individual sessions are overlaid. Dashed and dotted lines mark reference values.

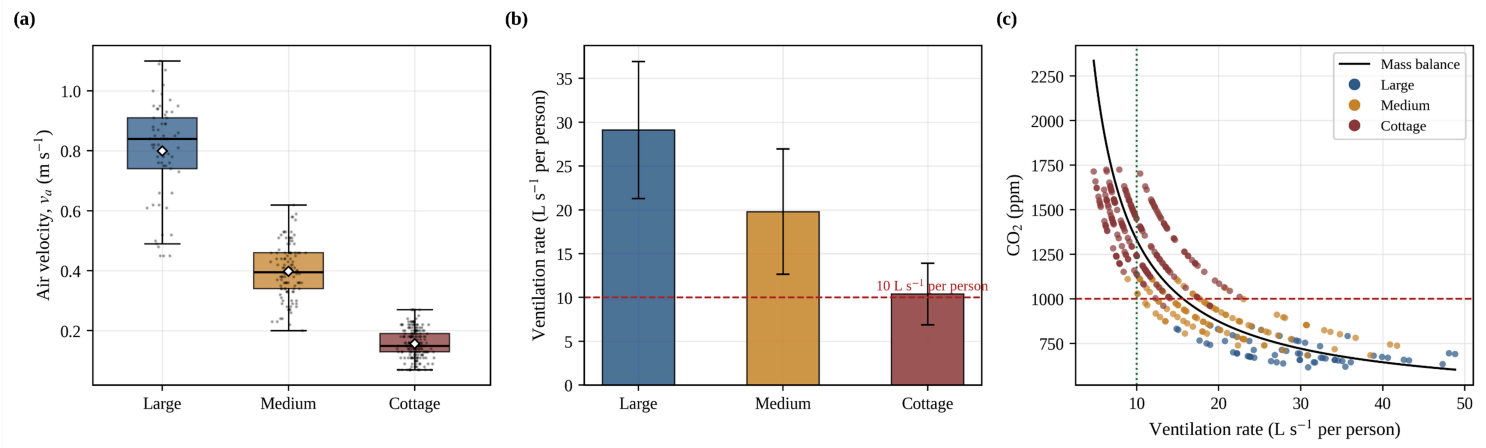


Figure 3

Air movement and ventilation: (a) air velocity by enterprise tier; (b) derived ventilation rate per person with the 10 L s^{-1} benchmark, error bars showing one standard deviation; (c) measured CO_2 against derived ventilation rate with the steady-state mass-balance curve.

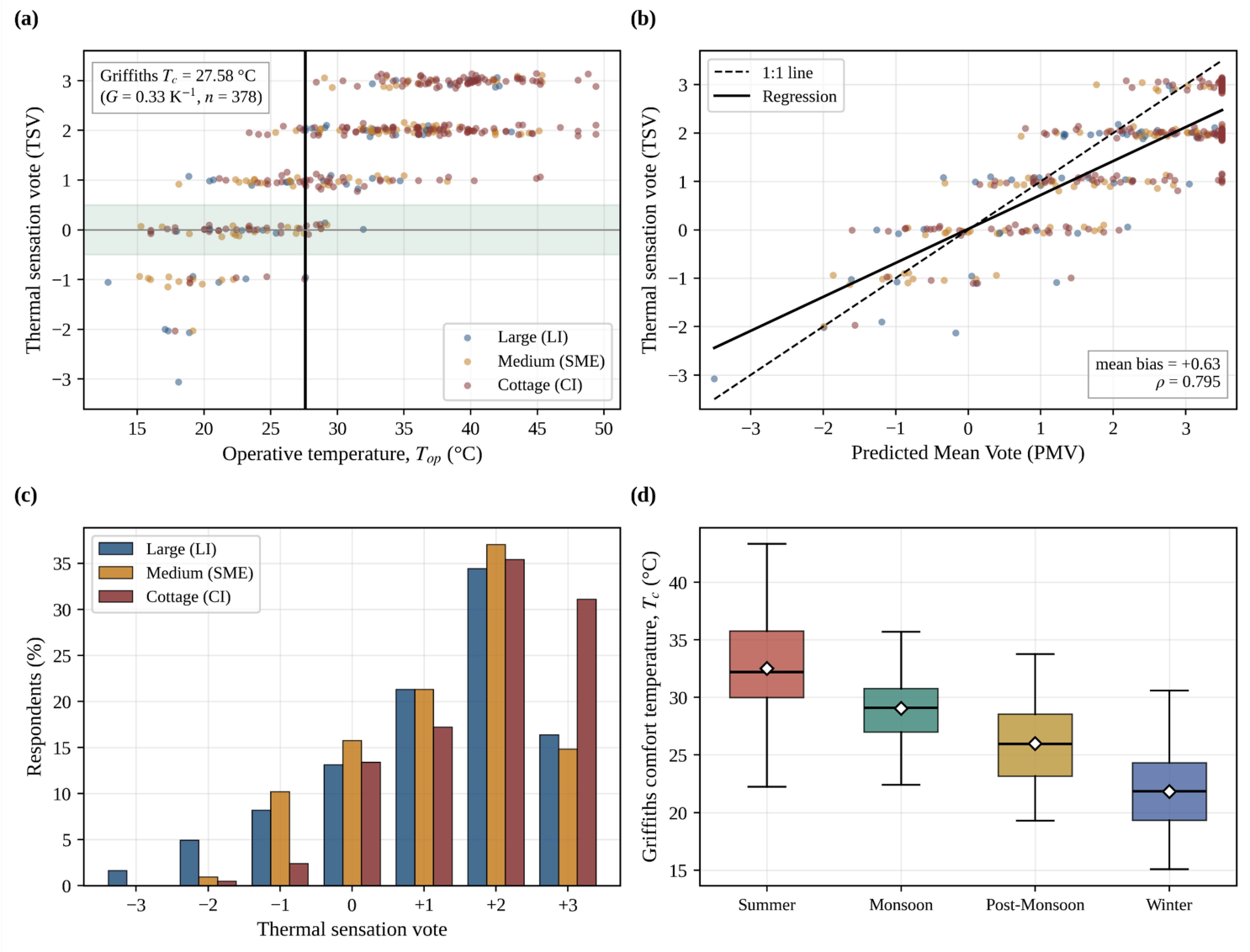


Figure 4

Thermal comfort: (a) thermal sensation vote against operative temperature, with the Griffiths comfort temperature marked and the ISO 7730 Category B vote band shaded; (b) reported sensation against Predicted Mean Vote with the identity line; (c) distribution of votes by tier; (d) Griffiths comfort temperature by season. Votes are jittered vertically for visibility.

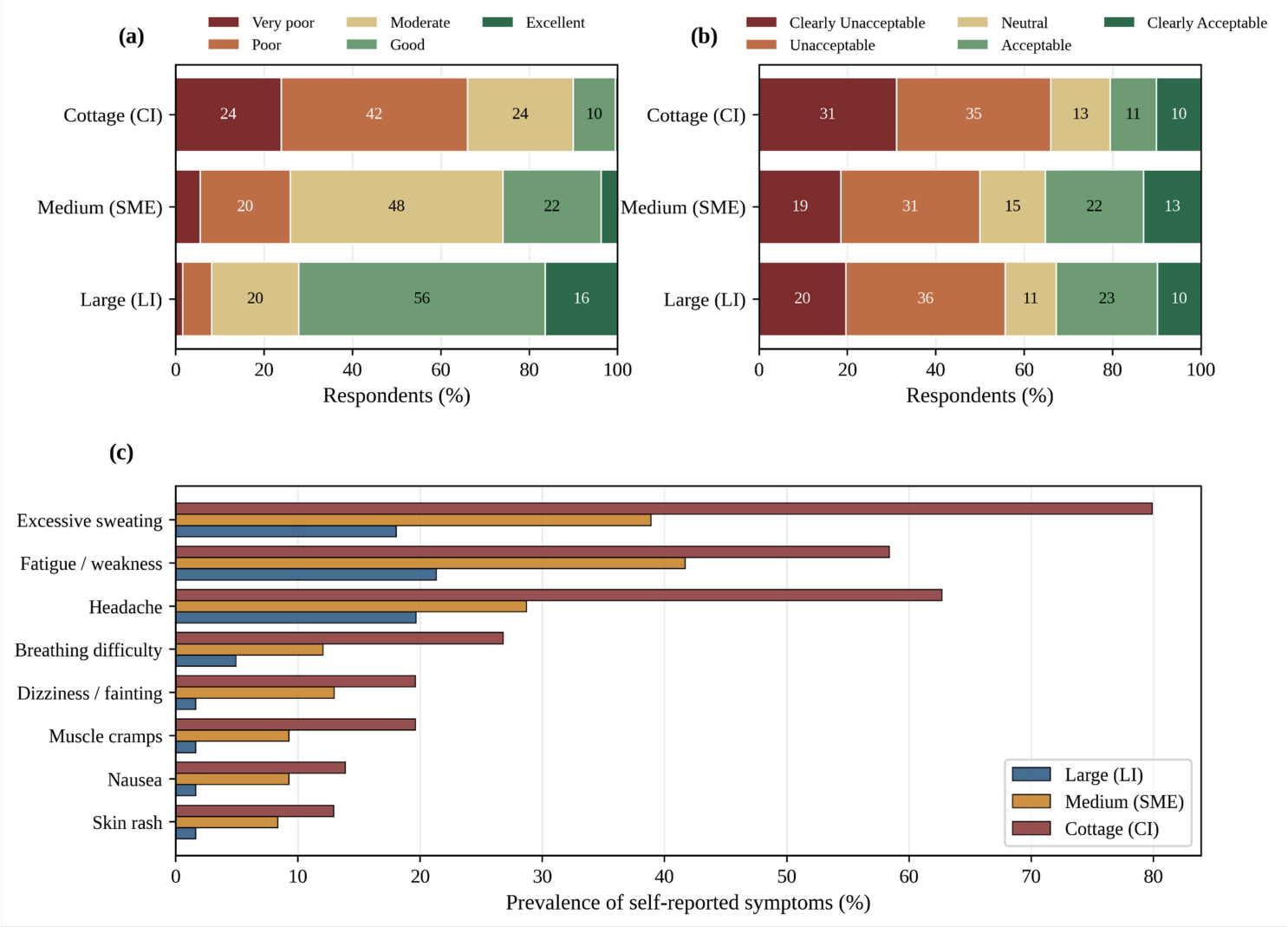


Figure 5

Occupant perception and reported symptoms: (a) perceived ventilation quality by tier; (b) thermal acceptability by tier; (c) prevalence of self-reported symptoms attributed to the working environment.

Supplementary Files

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