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Panich Intra

panich.intra@rmutl.ac.th

Rajamangala University of Technology Lanna

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Multi-point monitoring of PM₁₀, PM_{2.5}, and PM_{1.0} at a combined-cycle power plant: field agreement between four co-deployed electrostatic monitors

Panich Intra

Research Unit of Applied Electric Field in Engineering, College of Integrated Science and Technology,
Rajamangala University of Technology Lanna, Chiang Mai 50220, Thailand

Corresponding author: Panich Intra, panich.intra@rmutl.ac.th

ORCID: 0000-0002-2178-3898

Abstract

Thermal power plants are workplaces in which staff spend shifts in outdoor and semi-enclosed areas, yet continuous, size-resolved monitoring of airborne particulate matter (PM) inside plant boundaries is rarely available at more than one point. Four prototype three-channel electrostatic mass monitors, each combining unipolar corona charging, inertial-impaction size separation, and Faraday-cup electrometry, were adapted to measure PM₁₀, PM_{2.5}, and PM_{1.0} and installed at a combined-cycle power plant in Samut Prakan Province, Thailand. They operated from 1 February to 11 June 2020 with 92% to 100% daily data recovery. Station-mean concentrations were 44.9 to 54.1 $\mu\text{g}/\text{m}^3$ (PM₁₀), 24.8 to 30.8 $\mu\text{g}/\text{m}^3$ (PM_{2.5}), and 7.5 to 11.9 $\mu\text{g}/\text{m}^3$ (PM_{1.0}), peaking in February and showing no weekday-weekend contrast. Because four units of one design sampled the same air mass simultaneously, their agreement could be measured directly. Fixed differences between stations accounted for only 0.7% of the variance in the log-transformed 24-h PM₁₀ concentrations, but the day-by-station interaction accounted for 57.1%, and the 95% limits of agreement between station pairs spanned 0.35 to 3.26 for PM₁₀ and 0.33 to 2.83 for PM_{2.5}. The intraclass correlation for a single unit was 0.42 for PM₁₀, rising to 0.75 for the mean of all four. The disagreement did not diminish under temporal averaging and was not confined to one unit, pointing to time-varying, unit-specific behaviour rather than micro-scale spatial variation. Multi-point deployments of this class of instrument therefore support pooled and time-averaged comparisons but not comparisons between individual stations, unless co-location checks are built into the campaign.

Keywords Aerosols · air pollutants · corona discharge · instrument reproducibility · particle sensing · Thailand

Introduction

A combined-cycle power plant is, before anything else, a workplace: operations, maintenance, and contractor personnel spend working shifts in outdoor and semi-enclosed areas around the turbine hall, the air-intake structures, and the fuel and cooling systems, so the ambient particulate matter (PM) concentration at those locations is the airborne exposure environment of that workforce. Personal sampling characterises what an individual breathes over a shift, but it cannot be run continuously for months at a time; fixed-point area monitoring can, and it is the practical route to knowing when and where in a plant the airborne burden rises. In Thailand, long-term exposure to ambient PM_{2.5} has been estimated to account for approximately 50,000 deaths and 509,000 disability-adjusted life years in a

single year (Mueller et al., 2021), and personal monitoring of outdoor workers in central Bangkok has recorded working-day PM_{2.5} exposures averaging about 44 µg/m³, above both the national and the World Health Organization (WHO) 24-h values (Archer et al., 2024). Continuous, size-resolved area monitoring at several points inside a plant boundary therefore addresses a recognised gap in occupational and environmental hygiene practice at large industrial sites, where such records are rarely available at better than 24-h resolution or at more than one point.

The same measurement serves a second purpose at this class of facility. Combined-cycle power plants recover the heat energy of gas-turbine exhaust, typically at approximately 500 °C, in a heat-recovery steam generator that raises steam for an auxiliary steam turbine, giving substantially higher overall thermal efficiency than a simple gas-turbine cycle alone. Reliable operation of the gas-turbine section, however, depends on the cleanliness of the air drawn through its inlet filtration system: PM accumulating on inlet filters, and any that penetrates them onto compressor blades, increases inlet differential pressure and compressor fouling, both of which reduce power output and thermal efficiency and increase fuel consumption and carbon dioxide-equivalent emissions per unit of electricity generated. In a recent machine-learning analysis of 4438 h of base-load operating data from an industrial gas turbine, each 1 mbar increase in inlet-filter differential pressure was associated with an average 1.67 MW reduction in power output and a 0.094-percentage-point reduction in thermal efficiency (Büyükköse & Aslan, 2026). Quantifying the particulate loading responsible for this pressure rise, ideally at multiple points around a plant rather than from a single filter differential-pressure sensor alone, is therefore of direct operational and economic relevance to power-plant operators, in addition to the ambient air-quality considerations that motivate PM monitoring more generally.

As in other PM-monitoring contexts, the instruments most commonly used for this purpose are beta-attenuation monitors, the tapered-element oscillating microbalance (TEOM), and dichotomous samplers of the general type specified in United States Environmental Protection Agency (EPA) reference-method regulations (EPA, 1997a, 1997b). These provide accurate mass-concentration data but are imported, expensive, and, for instruments with an oscillating or moving sensing element, potentially sensitive to the mechanical vibration present around large rotating machinery. Each instrument also typically reports only a single particle-size fraction, so obtaining PM₁₀, PM_{2.5}, and PM_{1.0} concurrently at each of several monitoring points around a power plant would, using conventional instrumentation, require a correspondingly large number of separate monitoring stations. Research-grade instruments exploiting particle electrical mobility (Keskinen, 1992) and, more recently, a large literature on low-cost optical (light-scattering) sensors (Morawska et al., 2018) offer alternative approaches with their own trade-offs in cost, accuracy, and field robustness; the electrostatic approach used here and in the earlier coal-mine study (Intra, 2018) occupies a comparatively narrow, but growing, niche within this wider set of alternatives.

The three size fractions measured here carry different information. PM₁₀ and PM_{2.5} are the fractions for which ambient standards and most epidemiological evidence exist, whereas the sub-micron fraction approximated by PM_{1.0} contributes little to total mass but deposits efficiently in the alveolar region (Hinds, 1999) and is not resolved by conventional PM_{2.5} or PM₁₀ monitoring. Reporting all three simultaneously at each measurement point therefore adds information that a single-fraction instrument cannot supply.

An electrostatic (charge-based) alternative to these reference methods has been developed and progressively validated over a series of studies (Intra, 2010; Intra & Tippayawong, 2011, 2013, 2015; Intra et al., 2012, 2013, 2016, 2018a, 2018b, 2021a, 2021b; Yawootti et al., 2015a, 2015b; Intra & Siri-achawawath, 2019). It culminated in a three-channel monitor combining unipolar corona charging, inertial-impaction size separation, and Faraday-cup electrometry to measure total suspended particulate (TSP), PM10, and PM2.5 simultaneously. That instrument was validated against five reference or equivalent instruments and operated for 12 months at the Mae Moh open-pit lignite mine in Lampang Province, Thailand, to characterise occupational dust exposure, yielding a 9-month continuous record from September 2017 to May 2018 (Intra, 2018). Intra (2018) is a final project report rather than a peer-reviewed publication and is cited here only to place the present instrument in its development lineage; no result reported in this paper depends on it. The design principles behind the instrument are documented in the peer-reviewed studies in the same lineage (Intra et al., 2012; Intra & Tippayawong, 2011, 2013, 2015; Yawootti et al., 2015a, 2015b; Intra et al., 2018b, 2021a, 2021b), and every design parameter, specification, and measurement value on which the present results depend is reported in full in this paper. Table 1 situates this lineage of studies, including the coal-mine study, relative to the present work.

Table 1 Comparison of the present study with prior electrostatic PM mass monitor development and validation studies

Study	Channel(s)	Test site	Reference instrument(s)	Duration	Key result
Intra et al. (2012)	PM2.5 (1)	Laboratory	—	—	Initial impactor/sampler design
Intra et al. (2013)	Particle number (1)	Roadside, Chiang Mai	Laser particle counter	~2 h	Good agreement (number concentration)
Yawootti et al. (2015b)	PM10, PM2.5 (2)	Ambient station	TEOM, Model 5014i	Field campaign	$R^2 = 0.9697$ (TEOM); $r = 0.9811$ (Model 5014i)
Intra et al. (2016)	PM10 (1)	School site, Chiang Mai	Model FH62C14	~3 weeks	$R^2 = 0.8634$ (1 h) [¶]
Intra et al. (2018a)	PM2.5 (1)	School site, Chiang Mai	Model 5014i	~3 weeks	Field evaluation
Intra et al. (2018b)	PM1.0, PM2.5, PM10 (3)	RUEE, Doi Saket	DustTrak	~4 days	High correlation
Intra and Siri-achawawath (2019)	PM10, PM2.5, sub-400 nm (3)	RUEE	NanoScan SMPS	Field campaign	Expanded to number and size distribution

Study	Channel(s)	Test site	Reference instrument(s)	Duration	Key result
Intra (2018)	TSP, PM10, PM2.5 (3; TSP new)	Doi Saket (validation); Mae Moh mine (deployment)	TEOM, Model 5014i, Model FH62C14, DustTrak, high-volume sampler (5)	Short campaign (validation); 12 months (deployment)	$r = 0.814\text{--}0.994$ across nine comparisons
This study	PM10, PM2.5, PM1.0 (3; PM1.0 new)	Doi Saket (validation, cited only); South Bangkok power plant, 4 simultaneous stations (deployment)	TEOM, Model 5014i, Model FH62C14, DustTrak (cited; no new comparison)	Short campaign (validation, cited); 132 days, 4 stations (deployment)	Field data only; no new correlation values

Note: The correlation range shown for Intra (2018) is the span of the nine reference and equivalent-instrument comparisons reported in that study (lowest, PM1.0 against the DustTrak photometer at 1 min, $r = 0.8144$; highest, PM10 against the Model FH62C14 monitor at 24 h, $r = 0.9944$). All entries above Intra (2018) correspond to peer-reviewed publications. Intra (2018) is a final project report delivered to the Electricity Generating Authority of Thailand and was not independently peer-reviewed; it is cited for development lineage only.

¶ Table 1 reports each result in the form published by its original source, whereas Table 3 reports correlation coefficients throughout; where a source published only a coefficient of determination, the corresponding r here is back-calculated as its square root. Intra et al. (2016) report a slope of 0.9620 with $R^2 = 0.8634$ for the 1-h comparison and a slope of 1.0649 with $R^2 = 0.9889$ for the 24-h comparison, corresponding to $r = 0.9292$ and $r = 0.9944$ respectively.

The present study adapts this same validated measurement platform to a different application and a different particle-size combination. Fouling of gas-turbine inlet filters and compressors is conventionally discussed in terms of PM10 and PM2.5 together with a sub-micron fraction, here approximated by PM1.0, rather than the unclassified TSP channel used for the occupational-exposure application of the coal-mine study. Accordingly, the third impactor stage was reconfigured from an unclassified TSP inlet to a PM1.0 inertial-impaction stage, while the PM10 and PM2.5 stages, the corona-charging unit, and the Faraday-cup electrometry retain the same design as reported previously (Intra & Tippayawong, 2013, 2015; Intra, 2018). The study tested the hypothesis that the charging, impaction, and Faraday-cup detection chain already validated for PM10 and PM2.5 could be transferred without modification to a PM10/PM2.5/PM1.0 configuration, and that four such units would operate unattended for 132 days in an active power-plant environment and resolve the temporal PM pattern at the site consistently with an independent government reference station. The specific objectives of this study were to (i) adapt the validated three-channel electrostatic platform to a PM10/PM2.5/PM1.0 configuration suited to gas-turbine air-inlet filter monitoring; (ii) document the reconfiguration of the third channel from TSP to PM1.0; and (iii) evaluate the long-term (132-day), multi-station field performance of four simultaneously deployed units at an operating combined-cycle power plant, including comparison with a nearby government reference station. Consistent with the coal-mine study (Intra, 2018), no new laboratory characterisation of the corona-charging unit and no new reference-instrument comparison specific to the power-plant deployment were carried out. The charging characteristics and reference-instrument correlations reported previously for the same charger and Faraday-cup design (Intra & Tippayawong,

2011; Yawootti et al., 2015a, 2015b; Intra et al., 2018b, 2021a, 2021b) are taken to apply to the PM10 and PM2.5 channels here, subject to the caveats set out under Limitations of the study.

Materials and methods

Instrument adaptation

The prototype instrument retains the overall architecture described in detail previously for the TSP/PM10/PM2.5 configuration (Intra, 2018). Sample air enters through a weatherproof inlet mounted 1.5–6 m above ground in accordance with Thailand Pollution Control Department (PCD) guidance (PCD, 2010), then passes a heat-exchanger and silica-gel conditioning stage that limits the stream to approximately 35 °C and $\leq 60\%$ relative humidity (RH). Charging is by a needle-to-tube unipolar corona charger with an ion-trap electrode (stainless-steel needle, 2.5 mm diameter, 10° tip angle; aluminium T-piece outer electrode, 6 mm inner diameter; polytetrafluoroethylene insulation), of the same high-penetration unipolar design characterised previously (Intra & Tippayawong, 2013) and based on established corona-discharge principles (Chang et al., 1995). Detection is by three parallel Faraday-cup electrometer channels. Each carries a 47 mm high-efficiency particulate air filter (EPM 2000, Whatman, Maidstone, UK) and a transimpedance electrometer built around an operational amplifier (LMC662, Texas Instruments, Dallas, TX, USA), with an input bias current of approximately 40 fA and a time constant of approximately 22 ms, following the Faraday-cup electrometer approach described previously (Intra & Tippayawong, 2015). Fig. 1 shows the schematic and Fig. 2 the completed prototype in the PM10/PM2.5/PM1.0 configuration used in this study; Table 2 summarises the design specification. Data are logged, controlled, and relayed over a third-generation cellular network to a web-based dashboard.

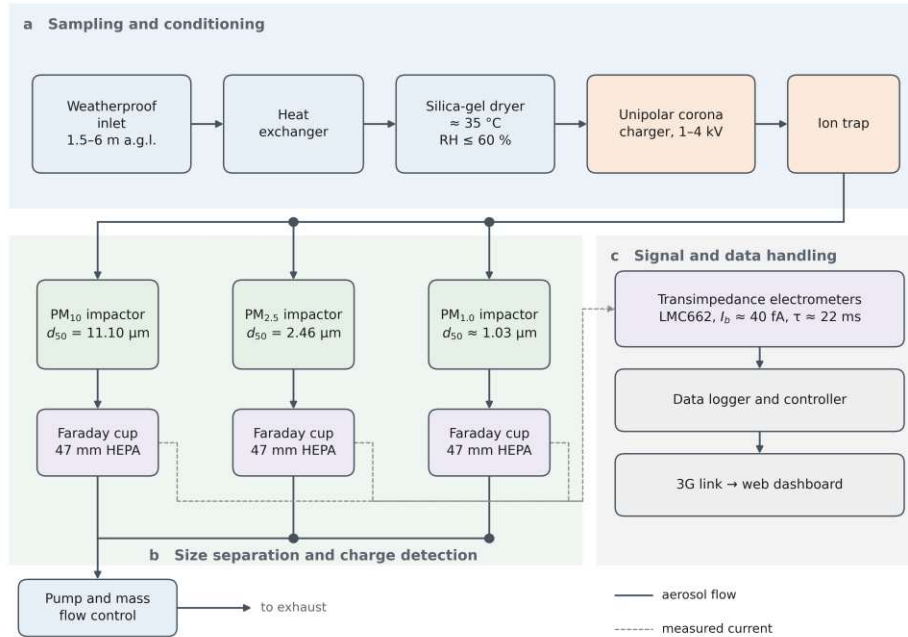


Fig. 1 Schematic of the prototype three-channel electrostatic monitor in its PM10/PM2.5/PM1.0 configuration: a sampling and conditioning; b size separation and charge detection; c signal and data handling. Solid lines are the

aerosol path and dashed lines the measured current. The architecture is unchanged from the earlier TSP/PM10/PM2.5 instrument (Intra, 2018); only the third channel differs, with a PM1.0 impactor stage in place of the unclassified TSP inlet. a.g.l., above ground level



Fig. 2 Photographs of the prototype in the PM10/PM2.5/PM1.0 configuration (enclosure $48.62 \times 22.15 \times 43$ cm): a internal layout, showing the three Faraday-cup assemblies with their impaction stages, the high-voltage supply, and the data-acquisition board; b the instrument installed in a monitoring shelter, with the conditioned sample line entering from the ceiling and the control and display computer alongside

Table 2 Design specification of the prototype in the PM10/PM2.5/PM1.0 configuration deployed in this study

Parameter	Specification
Measurement principle	Inertial-impaction size separation with electrostatic (corona) charge detection; unchanged from Intra (2018)
Particle size fractions	PM10, PM2.5, PM1.0 (3 simultaneous channels); PM1.0 stage newly configured for this study in place of the TSP channel used in Intra (2018)
Mass-concentration range	0.1–4000 $\mu\text{g}/\text{m}^3$
Resolution	0.1 $\mu\text{g}/\text{m}^3$
Sample flow rate	5 L/min per channel (15 L/min total)
Response time	< 1 s
Averaging intervals	30 min, 1 h, 8 h, 24 h
Inlet air temperature / humidity	20–50 $^{\circ}\text{C}$ / < 80% RH
Conditioned air temperature / humidity	~35 $^{\circ}\text{C}$ / $\leq$ 60% RH
Remote communication	Third-generation cellular network; web-browser display
Power supply	220 VAC, 50 Hz
Number of units deployed	4 (this study) against 1 (Intra, 2018)

RH, relative humidity; TSP, total suspended particulate; VAC, volts alternating current.

Particles entering the charging zone acquire charge predominantly by the diffusion of unipolar ions. For particles large relative to the ion mean free path the mean number of elementary charges acquired is described by the diffusion-charging relation of Equation 1 (Hinds, 1999; Intra & Tippayawong, 2011):

$$n(d) = (2 \pi \epsilon_0 d k T / e^2) \ln[1 + (d c_i e^2 N_i t) / (8 \epsilon_0 k T)] \quad (1)$$

where n is the mean number of elementary charges carried by a particle of diameter d , ϵ_0 the permittivity of free space, k the Boltzmann constant, T the absolute temperature, e the elementary charge, c_i the mean thermal speed of the ions, and $N_i t$ the product of ion number concentration and residence time in the charging zone. The ion concentration is set by the corona voltage, which is why that voltage is held within the 1–4 kV range characterised for this ionizer design (Intra & Tippayawong, 2013).

Charged particles are collected on the Faraday-cup filter of each channel, and the charge they deposit appears as a current, given by Equation 2:

$$I = n e N Q \eta \quad (2)$$

where I is the current collected at the Faraday cup, N the particle number concentration, Q the volumetric sample flow rate through the channel, and η the combined penetration and collection efficiency of that channel; n and e are as defined for Equation 1. The current is converted to a voltage by a transimpedance amplifier, following Equation 3:

$$V = -I R_f, \quad \tau = R_f C_f \quad (3)$$

where V is the amplifier output voltage, R_f the feedback resistance, C_f the feedback capacitance, and τ the resulting time constant. The values quoted above, a time constant of approximately 22 ms and an input bias current of approximately 40 fA, correspond to the components used here. The mass concentration of a size fraction follows from its number concentration through Equation 4:

$$C = (\pi/6) \rho_p d^3 N = (\pi \rho_p d^3 I) / (6 n e Q \eta) \quad (4)$$

where C is the mass concentration, ρ_p the particle density, and d here the effective diameter representing the fraction rather than the diameter of an individual particle as in Equation 1; N , I , n , e , Q , and η are as defined above. The quantities in Equation 4 that are not measured directly, namely the effective diameter, the particle density, and the charging and transport efficiencies, are collected into a single mass-current calibration factor K , so that the reported concentration is obtained from Equation 5 as:

$$C = K I / Q \quad (5)$$

where K is the mass-current calibration factor for the channel. K is determined empirically by comparison against reference instruments rather than computed from first principles (Fig. 3). Because Equation 4 shows K to depend on the size distribution and density of the sampled aerosol as well as on the charging efficiency, it is in principle site-specific, and the consequences of applying a factor derived at other sites are considered under Limitations of the study.

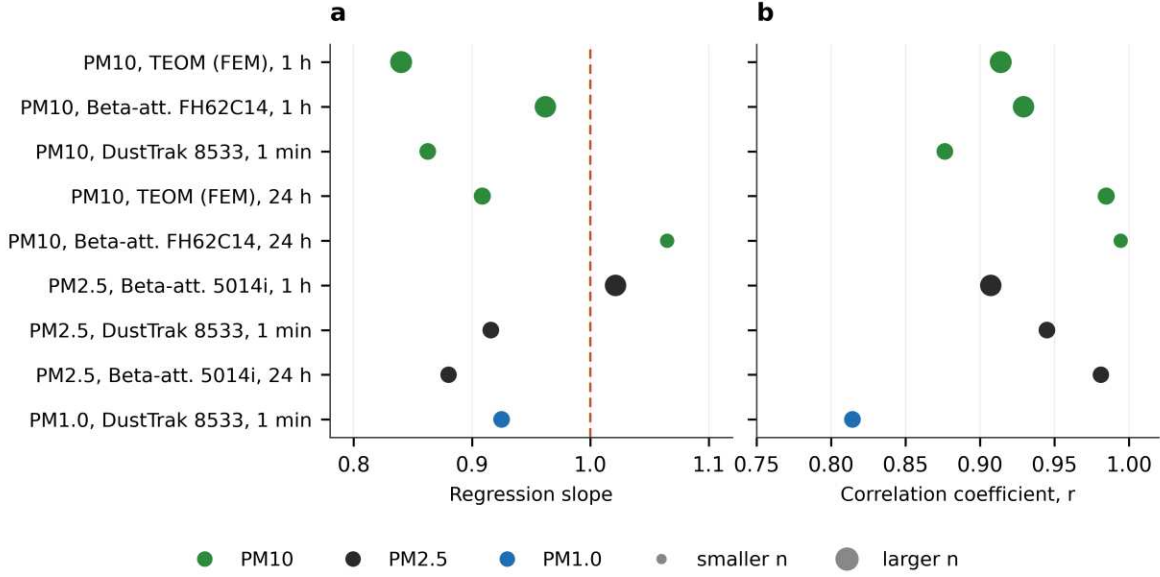


Fig. 3 Reference-instrument comparisons reported for this measurement platform in earlier studies. a Regression slope of the electrostatic monitor against each reference or equivalent instrument, with the dashed line marking a slope of unity. b Correlation coefficient for the same comparisons. Marker area scales with the number of paired observations, which ranged from 7 to 723. Values are reproduced from the published sources and were not re-derived here

Reconfigured impactor stage (PM1.0 in place of TSP)

The PM10 and PM2.5 inertial-impaction stages are unchanged from the previous design (Intra, 2018), with 50% cut-point aerodynamic diameters of 11.10 μm and 2.46 μm , respectively, at the design flow of 5 L/min per stage. Each stage was sized by the classical Stokes-number method, in which the 50% cut-point aerodynamic diameter of a round-jet impactor is given by Equation 6 (Hinds, 1999):

$$d_{50} = [9 \mu W \text{Stk}_{50} / (\rho_p C_c U)]^{1/2} \quad (6)$$

where d_{50} is the 50% cut-point aerodynamic diameter, μ the dynamic viscosity of air, W the acceleration-nozzle diameter, Stk_{50} the Stokes number at the cut-point (0.24 for round jets), ρ_p the particle density, C_c the Cunningham slip correction factor, and U the jet velocity. The relation is expressed in aerodynamic rather than geometric diameter because impaction is governed by particle inertia. The jet velocity follows from the channel flow rate and the nozzle diameter (Equation 7), and the slip correction from the particle diameter and the mean free path λ of air (Equation 8):

$$U = 4Q / (\pi W^2) \quad (7)$$

$$C_c = 1 + (\lambda/d)[2.34 + 1.05 \exp(-0.39 d/\lambda)] \quad (8)$$

where λ is the mean free path of the air molecules, taken as 0.066 μm at 293 K and 101.3 kPa, and d the particle diameter (Hinds, 1999). Equations 6 and 7 together give d_{50} proportional to Q raised to the power minus one half, so the cut-points quoted here apply at the design channel flow of 5 L/min (15 L/min for the three channels combined);

Table 2). The third channel, previously an unclassified TSP inlet, was reconfigured for this study into an inertial-impaction stage targeting a PM1.0 ($\approx 1 \mu\text{m}$) 50% cut-point, using an acceleration-nozzle diameter and jet velocity intended to follow the same Stokes-number procedure. The design documentation for the instrument gives acceleration-nozzle diameters of 2.8 and 7.0 mm and nozzle-to-plate distances of 10 and 9.5 mm for what are described as three channels, so a separate, dedicated nozzle geometry for the PM1.0 stage is not unambiguously documented; the resulting $\approx 1.03 \mu\text{m}$ cut-point reported here is therefore provisional pending confirmation of the as-built PM1.0 nozzle dimensions (see Limitations of the study).

Reference-instrument comparison reported in prior work

Correlation of this measurement platform against reference and equivalent-method instruments has been reported previously (Yawootti et al., 2015b; Intra et al., 2016, 2018b). The instruments were a TEOM (Thermo Fisher Scientific, Waltham, MA, USA) for PM10, beta-attenuation monitors (Models 5014i and FH62C14, Thermo Fisher Scientific, Waltham, MA, USA) for PM2.5 and PM10, and a light-scattering photometer (DustTrak DRX 8533, TSI Incorporated, Shoreview, MN, USA) for PM1.0, PM2.5, and PM10. The regression slope and the correlation coefficient of each comparison are shown in Fig. 3, with marker area scaled to the number of paired observations; the full detail, including the intercepts, is given in Table 3. Table 1 reports each summary statistic in the form published by its original source, whereas Table 3 reports correlation coefficients throughout; where a source published only a coefficient of determination, the corresponding r in Table 3 is back-calculated. Only the comparisons relevant to the size fractions measured here are reproduced; the earlier TSP channel has no counterpart in the present configuration and is not considered further.

Table 3 Reference and equivalent-instrument comparison statistics attributed to this measurement platform in prior work (Yawootti et al. 2015b; Intra et al. 2016, 2018b), compiled for the present paper from those three sources; not independently re-derived here

Size fraction	Reference / equivalent instrument	Averaging	n	Slope	Intercept	r
PM10	TEOM (FEM)	1 h	723	0.8401	6.99	0.9139†
PM10	TEOM (FEM)	24 h	31	0.9087	4.02	0.9847†
PM2.5	Beta-attenuation (Model 5014i)	1 h	507	1.0213	-0.63	0.9072†
PM2.5	Beta-attenuation (Model 5014i)	24 h	21	0.8802	2.75	0.9811
PM10	Beta-attenuation (Model FH62C14)	1 h	512	0.9620	-0.11	0.9292†¶
PM10	Beta-attenuation (Model FH62C14)	24 h	7	1.0649	-3.73	0.9944†¶
PM1.0	Light-scattering (DustTrak 8533)	1 min	24	0.9250	1.85	0.8144§

Size fraction	Reference / equivalent instrument	Averaging	n	Slope	Intercept	r
PM2.5	Light-scattering (DustTrak 8533)	1 min	24	0.9159	3.97	0.9449 [‡]
PM10	Light-scattering (DustTrak 8533)	1 min	24	0.8626	6.01	0.8764 [‡]

FEM, federal equivalent method; TEOM, tapered-element oscillating microbalance.

[†] r back-calculated as the square root of R^2 for every row so marked, where the original source reported only a coefficient of determination rather than r directly. This recovers the magnitude of r but not its sign, and a positive sign is assumed throughout, consistent with these being physical mass-concentration comparisons. Four-decimal precision on these values should not be read as four-decimal confidence.

[§] This value could not be cross-checked against a source plot at the time of writing and should likewise be treated as approximate despite the precision shown.

[‡] These DustTrak values differ slightly from the originally published source for reasons that could not be established, and should be treated as approximate pending reconciliation.

[¶] See the note to Table 1. Given these caveats, and that several of the underlying comparisons rest on small samples ($n = 7$ –24 for the FH62C14 24-h, 5014i 24-h, and all three DustTrak comparisons), the correlation statistics in Table 3 should be read as indicative of the general performance of the measurement approach rather than as precise, fully audited figures.

The regression detail in Table 3 was compiled from the three published sources named above rather than re-derived from their underlying data (Yawootti et al., 2015b; Intra et al., 2016, 2018b); of the nine comparisons in Fig. 3, only one (PM2.5 against the Model 5014i monitor, 24 h) carries no data-quality caveat, and this should be borne in mind when weighing how much confidence Fig. 3 can support. Twenty-four-hour correlations against the TEOM, Model 5014i, and Model FH62C14 monitors were consistently high ($r = 0.981$ – 0.994), comparable to levels reported for other reference-method PM inter-comparisons (Patashnick & Rupprecht, 1991; Koch et al., 1999; Babich et al., 2000; Lippmann et al., 2000; Misra et al., 2001; Liu et al., 2002). One-hour correlations were somewhat lower ($r = 0.907$ – 0.929). The 1-min DustTrak comparisons, based on smaller samples ($n \leq 24$) over a short co-location period, ranged from $r = 0.814$ to 0.945 . Because the charging, impaction (PM10 and PM2.5 stages), and Faraday-cup detection principles are unchanged from that earlier work, these correlations are taken to characterise the PM10 and PM2.5 channels of the present instrument and are not re-derived here. The DustTrak PM1.0 comparison in Fig. 3 was obtained for a different, non-impaction-classified photometer channel and does not verify the newly reconfigured PM1.0 impactor stage used here; no comparison of any kind exists yet for that stage (see Limitations of the study).

Field deployment

Four prototype units, designated EGAT1 to EGAT4, were installed at four locations within the South Bangkok combined-cycle power plant of the Electricity Generating Authority of Thailand (EGAT), Samut Prakan Province, Thailand (EGAT, 2026), and operated continuously for 132 days, from 1 February to 11 June 2020, logging hourly and 24-h average PM10, PM2.5, and PM1.0 concentrations (Fig. 4). Logging began during installation and commissioning in the last week of January 2020; the record analysed here begins on 1 February, and the commissioning days that precede it are used only for the reference-station comparison reported below. The stations

were distributed across the site rather than clustered (Fig. 5): EGAT1 stands in the main plant area, EGAT2 immediately beside the combined-cycle unit and its air-intake ductwork, EGAT3 near the oil-transfer pier on the river frontage, and EGAT4 at the high-voltage substation on the western side of the site. The four positions span the principal land uses inside the plant boundary. The campaign closed on 11 June 2020, when all four units were removed at the conclusion of the study; the absence of records after that date reflects the planned end of the deployment rather than lost data. The plant is situated within a mixed community and industrial area characteristic of Samut Prakan Province, with residential neighbourhoods and other industrial facilities located in the immediate vicinity of the site; this land-use context is referred to in interpreting the field results (see Discussion).

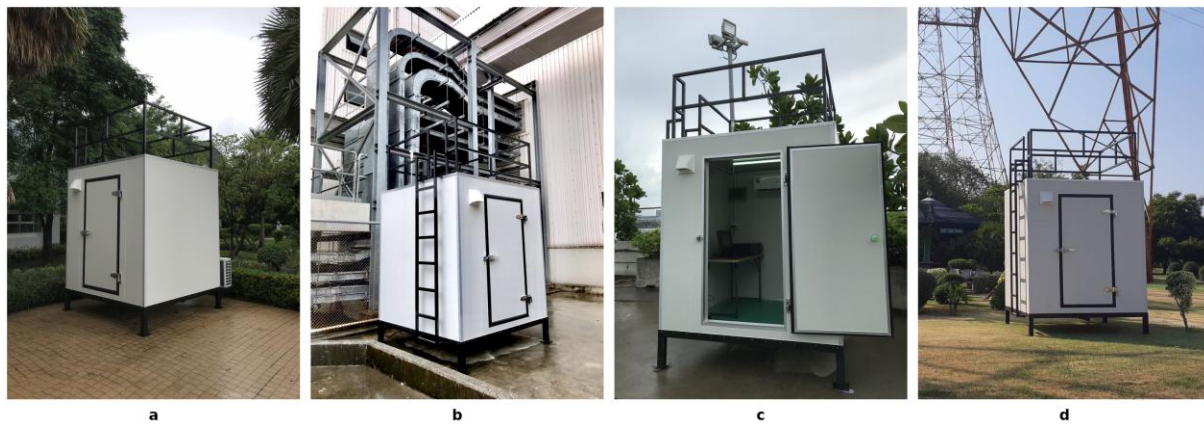


Fig. 4 The four monitoring stations, a EGAT1, b EGAT2, with the plant air-intake ductwork behind, c EGAT3, shown with the door open, and d EGAT4, with the transmission line behind. Each unit is housed in an air-conditioned shelter raised on a steel frame, with a railed roof platform reached by a fixed ladder that carries the sampling inlet at the 1.5–6 m height specified for ambient particulate sampling (PCD, 2010). Station locations within the site are shown in Fig. 5 and the interior of a shelter in Fig. 2b

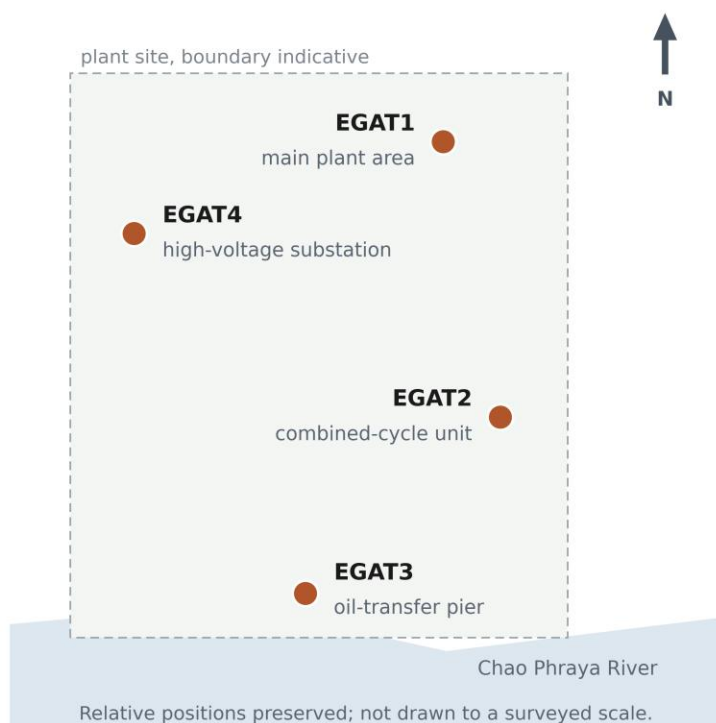


Fig. 5 Layout of the four monitoring stations within the South Bangkok combined-cycle power plant. Relative positions are preserved; the diagram is not drawn to a surveyed scale, and the site boundary and river frontage are indicative only

Periodic maintenance, including cleaning of the impaction plates, ion-trap electrodes, and Faraday-cup filters to remove particulate build-up accumulated during continuous field operation, was carried out at intervals throughout the campaign, and the affected unit was taken offline for the duration of each maintenance visit; this, together with fouling accumulating between visits, is the known source of the gaps in the record. The frequency, duration, and dates of these maintenance visits were not systematically logged, so individual outages cannot be attributed to specific visits; the resulting data recovery is nonetheless quantified from the screened 24-h record (see Results). Concentrations were additionally compared, on a qualitative basis, against those reported by the nearest PCD ambient monitoring station (PCD16); a formal statistical correlation between the prototype stations and PCD16 was not computed.

Data processing and quality screening

Each unit logged concentrations at hourly resolution. Two consistency checks were applied to the logged record before the 24-h averages analysed in this paper were formed. The first removed values above $100\,000\ \mu\text{g}/\text{m}^3$: three hours at EGAT1, on 17 February at 21:00 and 18 February at 08:00 and 12:00, in which the PM₁₀ channel returned $185\,200$, $382\,450$, and $224\,100\ \mu\text{g}/\text{m}^3$. These are 46 to 96 times the upper limit of the specified measurement range (Table 2), and the PM_{2.5} and PM_{1.0} channels registered nothing unusual in the same hours (12.0 , 27.8 , and $20.8\ \mu\text{g}/\text{m}^3$, and 3.0 , 6.5 , and $4.8\ \mu\text{g}/\text{m}^3$ respectively), so the excursions are treated as a fault confined to the PM₁₀

channel rather than as an atmospheric event; a combustion or biomass-smoke plume, in which the fine fraction dominates, would raise all three channels together.

The second check applied the physical-consistency criterion $PM_{1.0} \leq PM_{2.5} \leq PM_{10}$, which nested mass fractions satisfy by definition. The logged record failed it on 205 of 12 264 valid station-hours (1.7%), concentrated rather than scattered: 203 in February and 2 in May, none at EGAT1, representing 3.3% of EGAT2 hours, 2.3% of EGAT3 hours, and 1.2% of EGAT4 hours. At 24-h resolution the failures appear as eight station-days on which the $PM_{2.5}$ average exceeds the PM_{10} average by factors of 1.03 to 1.29 (EGAT2, 22–25 February; EGAT3, 27–29 February; EGAT4, 11 February), with every hour of each affected day failing the criterion and hourly ratios reaching 1.49. The pattern indicates sustained offsets of the PM_{10} channel rather than isolated recording errors. The hours concerned were retained rather than discarded, and the ordering was enforced on the PM_{10} channel, which the hourly pattern identifies as the affected one; the adjustment restores an ordering that must hold physically but does not recover the true PM_{10} values over the affected periods (see Limitations of the study). After the removal of the three out-of-range hours and this consistency adjustment, the record contains no value outside the specified measurement range and no station-hour failing the consistency criterion, no station-day is lost from the record, and the station mean concentrations move by at most $0.4 \mu\text{g}/\text{m}^3$.

Twenty-four-hour averages were then formed for each calendar day and station, and all results reported below are based on those averages; hourly values are not analysed further here. Concentrations were log-transformed before any variance or correlation analysis, since 24-h PM values are approximately log-normal. Daily PM series are strongly autocorrelated, so tests that assume independent observations overstate the evidence; every confidence interval and p value reported here is therefore computed on an effective sample size $n_{\text{eff}} = n(1 - a_1)/(1 + a_1)$, where a_1 is the lag-1 autocorrelation of the series concerned. Where two error-prone measurements are regressed on one another, the errors-in-variables (Deming) slope is used rather than ordinary least squares, because neither station is a reference. Screening, averaging, and plotting were carried out with standard statistical software. The descriptive statistics reported are arithmetic means, sample standard deviations, data-recovery counts, and counts of days exceeding fixed threshold values; the inferential procedures are the variance-component decomposition, the intraclass correlation, the Bland-Altman limits of agreement, the Deming regression, and the Mann-Whitney U test, each computed on the effective sample size defined above wherever a confidence interval or a p value is reported. No result depends on a feature specific to any one software package.

Results

Reconfigured $PM_{1.0}$ stage

A schematic and photographs of the reconfigured three-channel prototype, including the $PM_{1.0}$ stage, are shown in Figs. 1 and 2, and the resulting design specification is summarised in Table 2. No stage-specific collection-efficiency curve, and no computational fluid dynamics or scanning electron microscopy verification isolated to the $PM_{1.0}$ channel, analogous to the verification reported previously for the PM_{10} and $PM_{2.5}$ stages (Intra, 2018), were obtained for the reconfigured stage.

Campaign summary

Fig. 6 summarises the 24-h average PM10, PM2.5, and PM1.0 record at the four stations over the 132-day deployment (1 February to 11 June 2020), by station in panels a and b and by month in panels c and d. Fig. 7 shows the corresponding daily time series at all four stations, and the individual months are shown for February (Fig. 8), March (Fig. 9), April (Fig. 10), May (Fig. 11), and June (Fig. 12).

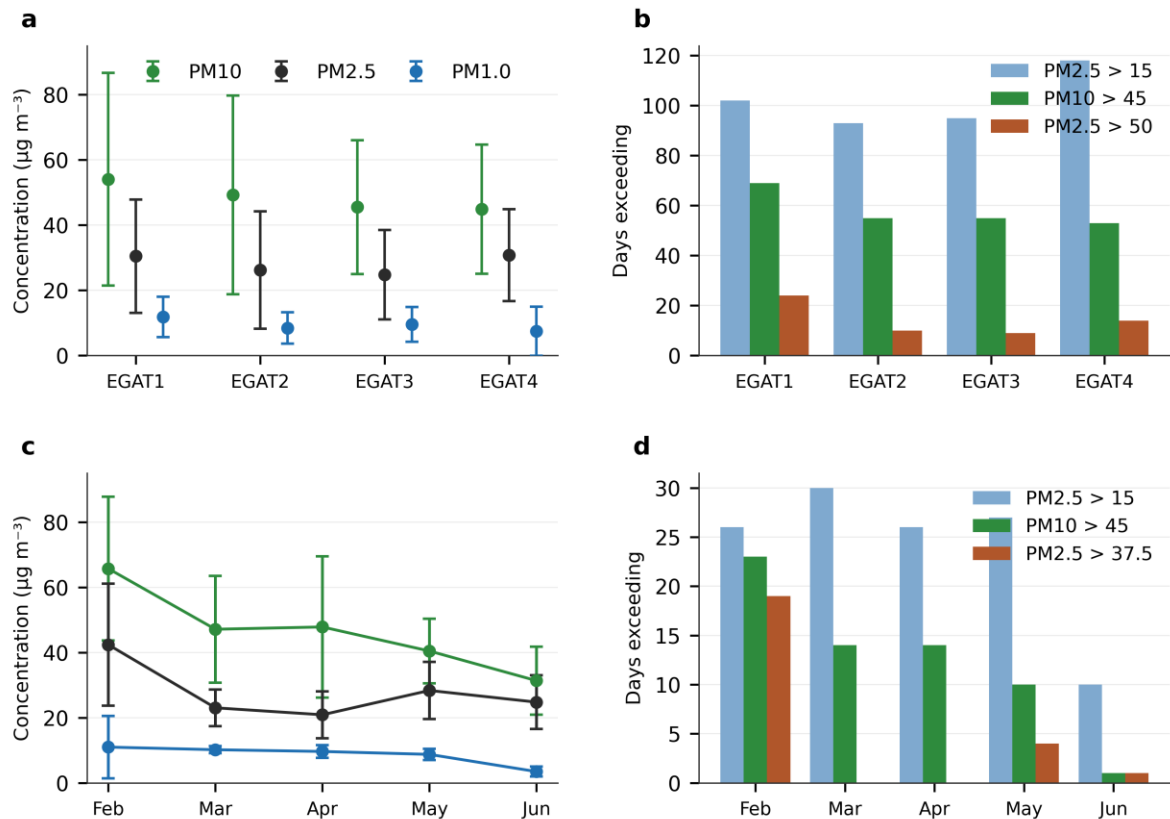


Fig. 6 Summary of the 24-h record over the campaign. a Station mean concentration with one standard deviation for each size fraction. b Number of days on which each station exceeded the World Health Organization 24-h guideline values for PM2.5 and PM10 and the Thai 24-h value for PM2.5 in force during the campaign. c Monthly mean of the four-station daily mean, with one standard deviation. d Number of days per month on which the four-station daily mean exceeded each value, with the Thai PM2.5 value now in force ($37.5 \mu\text{g m}^{-3}$) in place of the value then in force

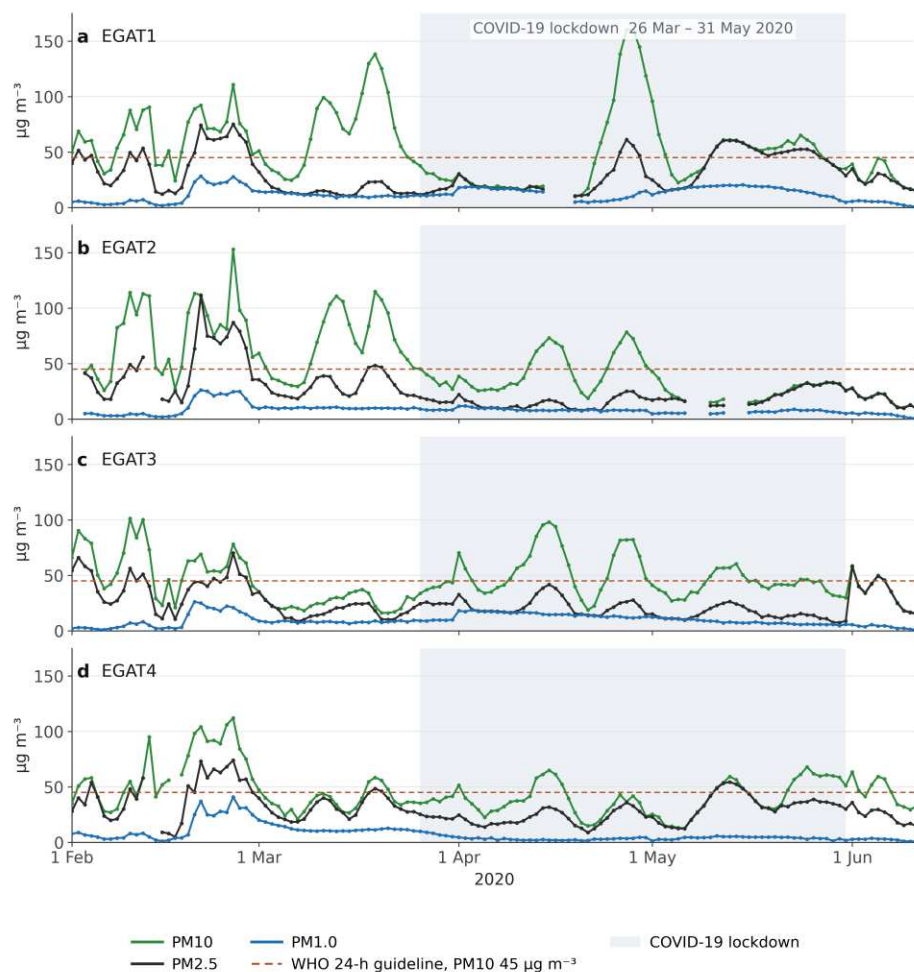


Fig. 7 Twenty-four-hour average PM10, PM2.5, and PM1.0 concentrations at stations a EGAT1, b EGAT2, c EGAT3, and d EGAT4 over the whole campaign, 1 February to 11 June 2020. The dashed line is the World Health Organization 24-h guideline value for PM10 ($45 \mu\text{g}/\text{m}^3$). Shading marks the nationwide COVID-19 lockdown and curfew of 26 March to 31 May 2020. Breaks in the traces are days with no valid record

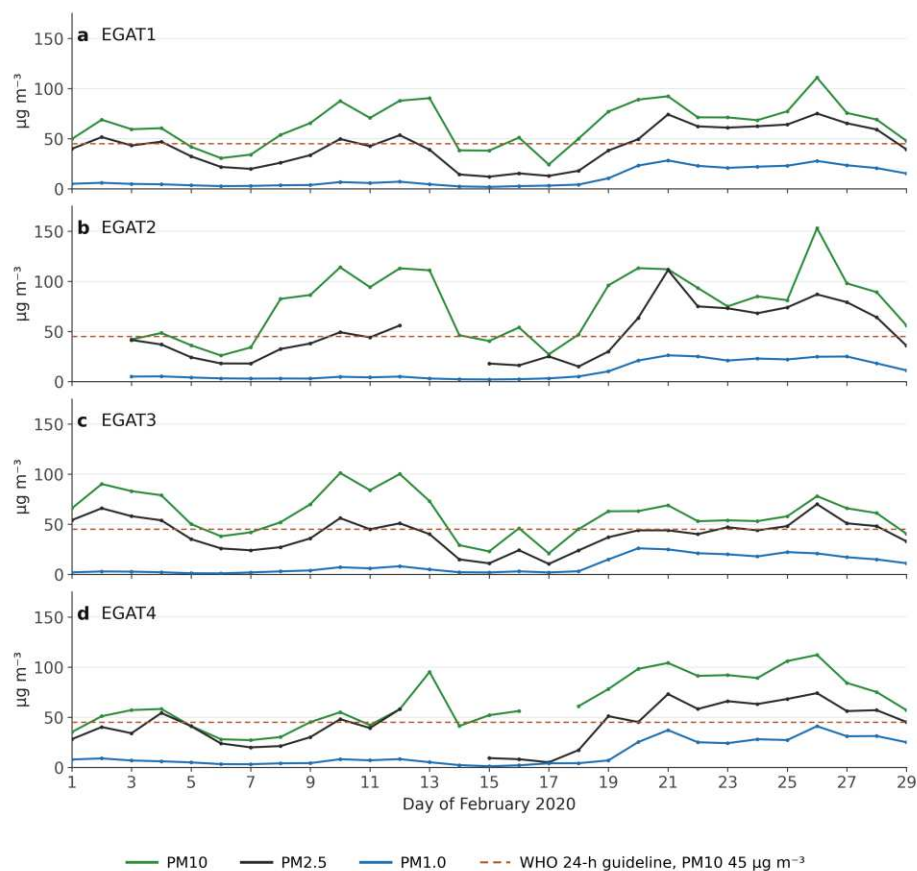


Fig. 8 Twenty-four-hour average PM10, PM2.5, and PM1.0 concentrations at stations a EGAT1, b EGAT2, c EGAT3, and d EGAT4, February 2020 (29 days). The peak month of the record. The dashed line is the World Health Organization 24-h guideline value for PM10 ($45 \mu\text{g}/\text{m}^3$)

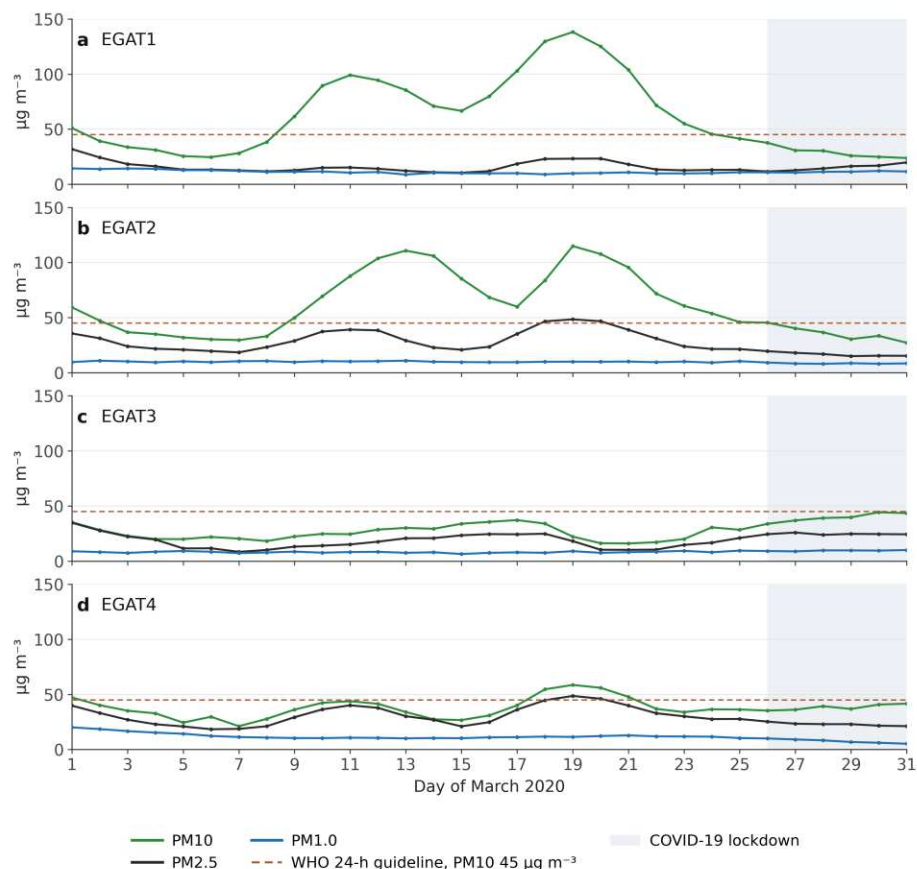


Fig. 9 Twenty-four-hour average concentrations at the four stations, March 2020 (31 days). Panels and conventions as in Fig. 8

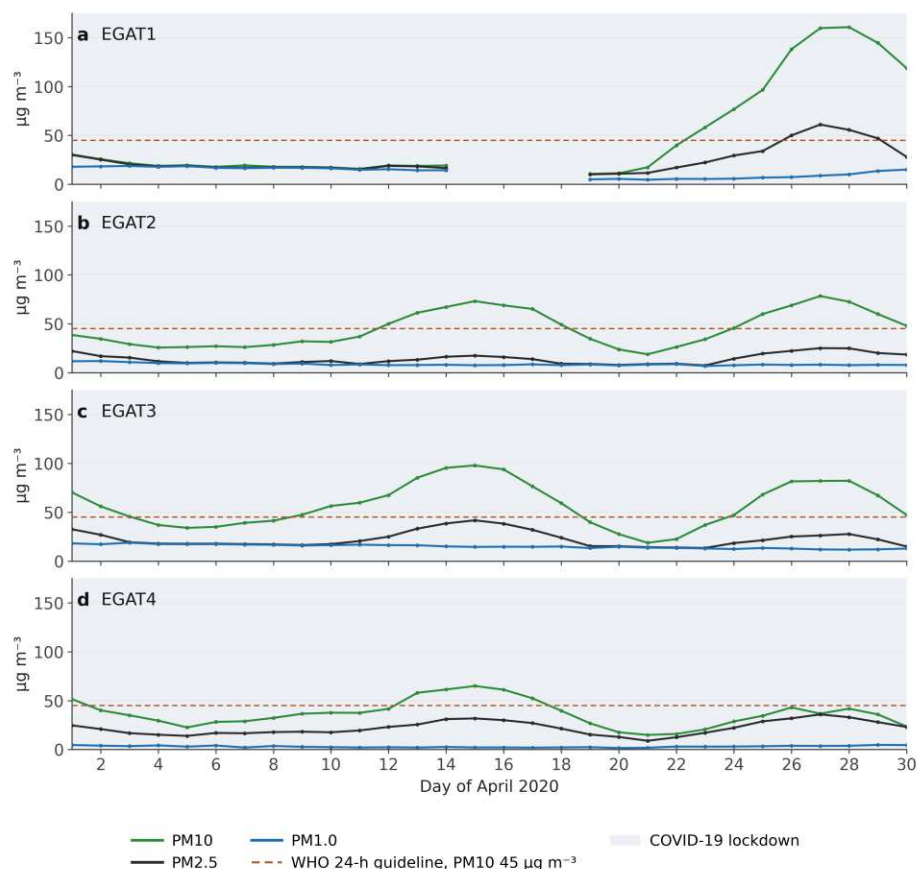


Fig. 10 Twenty-four-hour average concentrations at the four stations, April 2020 (30 days). Panels and conventions as in Fig. 8

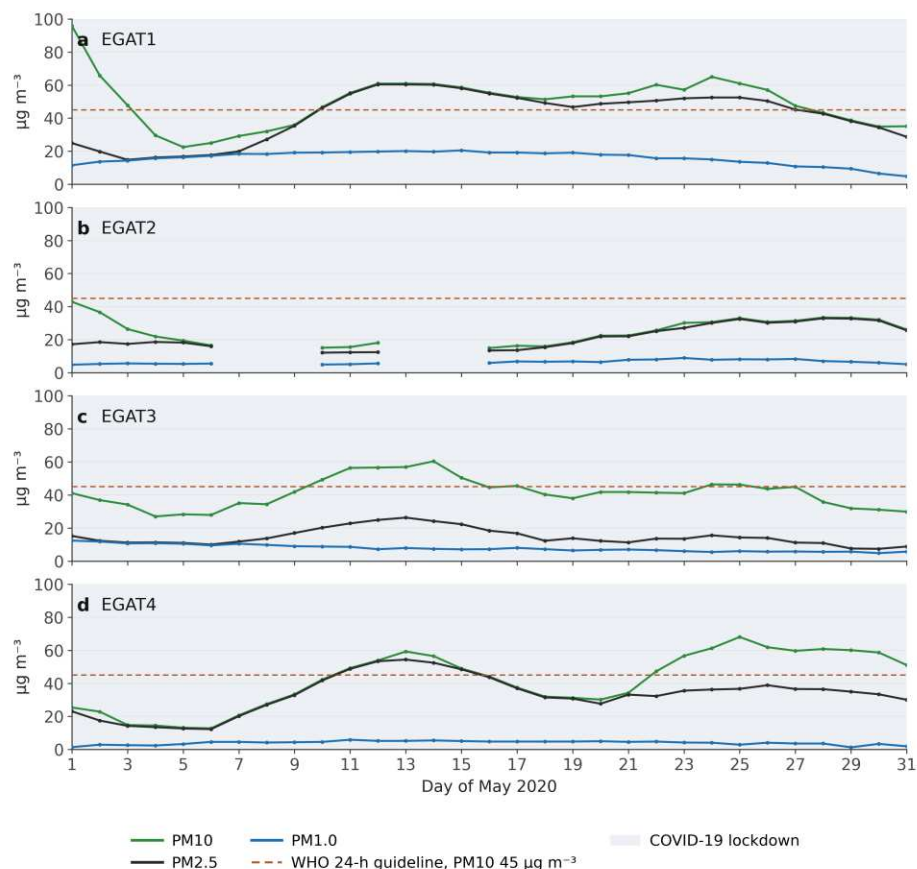


Fig. 11 Twenty-four-hour average concentrations at the four stations, May 2020 (31 days). Panels and conventions as in Fig. 8

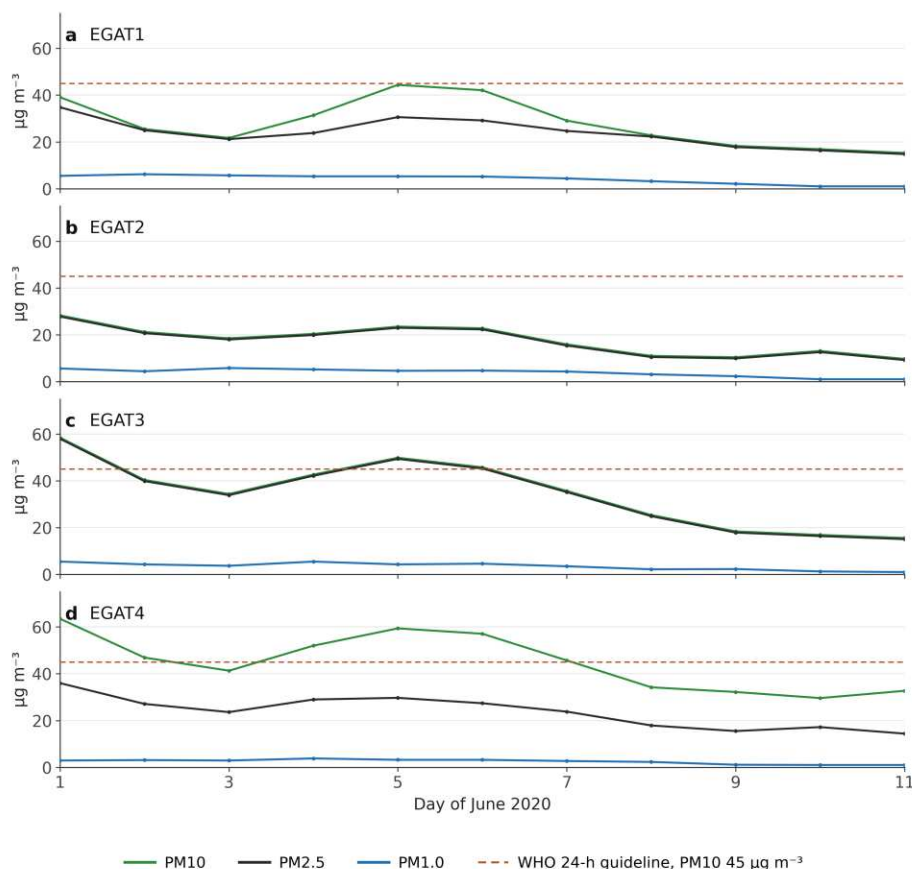


Fig. 12 Twenty-four-hour average concentrations at the four stations, June 2020 (11 days). Panels and conventions as in Fig. 8

Station-mean concentrations ranged from 44.9 to 54.1 $\mu\text{g}/\text{m}^3$ (PM10), 24.8 to 30.8 $\mu\text{g}/\text{m}^3$ (PM2.5), and 7.5 to 11.9 $\mu\text{g}/\text{m}^3$ (PM1.0), with the highest single 24-h averages reaching 160.8, 111.2, and 41.0 $\mu\text{g}/\text{m}^3$ respectively and the lowest 9.7, 5.0, and 1.0 $\mu\text{g}/\text{m}^3$ (Fig. 6). Mean PM2.5/PM10, PM1.0/PM2.5, and PM1.0/PM10 ratios were 53.2–68.6%, 24.3–38.9%, and 16.7–21.9% across the four stations. Concentrations were highest in February and declined thereafter toward the onset of the wet season, although the decline was monotonic only for PM10 and PM1.0 (Fig. 6).

Data recovery, monthly pattern, and standard exceedances

The record ends on 11 June 2020 at all four stations simultaneously, giving a campaign of 132 days. Daily data recovery over those 132 days was 122 to 132 days per station and fraction, that is 92% to 100%, and a four-station daily mean could be formed on every one of the 132 days. The shortfall within the campaign corresponds to the maintenance downtime and instrument fouling described under Materials and methods; the absence of records after 11 June reflects the planned end of the deployment.

The monthly means in Fig. 6 show February as the dominant month of the record (four-station mean PM10 65.7 $\mu\text{g}/\text{m}^3$, PM2.5 42.4 $\mu\text{g}/\text{m}^3$), followed by a decline that is monotonic for PM10 and PM1.0 from March to June but

not for PM2.5, which fell to a minimum of 20.9 $\mu\text{g}/\text{m}^3$ in April (Fig. 10) and rose again to 28.3 $\mu\text{g}/\text{m}^3$ in May (Fig. 11) before falling to 24.8 $\mu\text{g}/\text{m}^3$ in June (Fig. 12). PM1.0 fell sharply in June, to 3.5 $\mu\text{g}/\text{m}^3$ against 8.7 $\mu\text{g}/\text{m}^3$ in May, although the June figure rests on the 11 days before the record ends and is not a full-month value.

Against the Thai 24-h values in force during the campaign, PM10 exceeded 120 $\mu\text{g}/\text{m}^3$ on 8 of 515 valid station-days and PM2.5 exceeded 50 $\mu\text{g}/\text{m}^3$ on 57 of 512 valid station-days. Against the WHO 24-h guideline values, PM10 exceeded 45 $\mu\text{g}/\text{m}^3$ on 232 of 515 station-days and PM2.5 exceeded 15 $\mu\text{g}/\text{m}^3$ on 408 of 512 station-days. Taking the four-station daily mean as a single series (132 valid days), PM2.5 exceeded the Thai value then in force on 12 days, the Thai value now in force (37.5 $\mu\text{g}/\text{m}^3$) on 24 days, and the WHO guideline value on 119 days, while PM10 exceeded the WHO guideline value on 62 days and the Thai value on none. Exceedances of the tighter Thai PM2.5 value were concentrated in February (19 of the 24 days; Fig. 6).

Agreement between the four units

The full 24-h record is shown station by station and day by day in Fig. 13, with concentration mapped to colour. Read down a column, the four cells give the four stations on one day; read across a row, they give one station through the campaign. Columns of near-uniform colour would indicate that the four units saw the same air on that day. February appears as a dark block in all three fractions and all four rows, and the decline from March onwards is visible as a general lightening, so the seasonal signal is common to the stations. Within that pattern the columns are mottled rather than uniform, and the mottling does not settle into a consistent light-to-dark ordering of the rows. PM1.0 is the exception: rows EGAT1 and EGAT3 stay darker than EGAT2 and EGAT4 through most of the campaign, which is the fixed station effect quantified below.

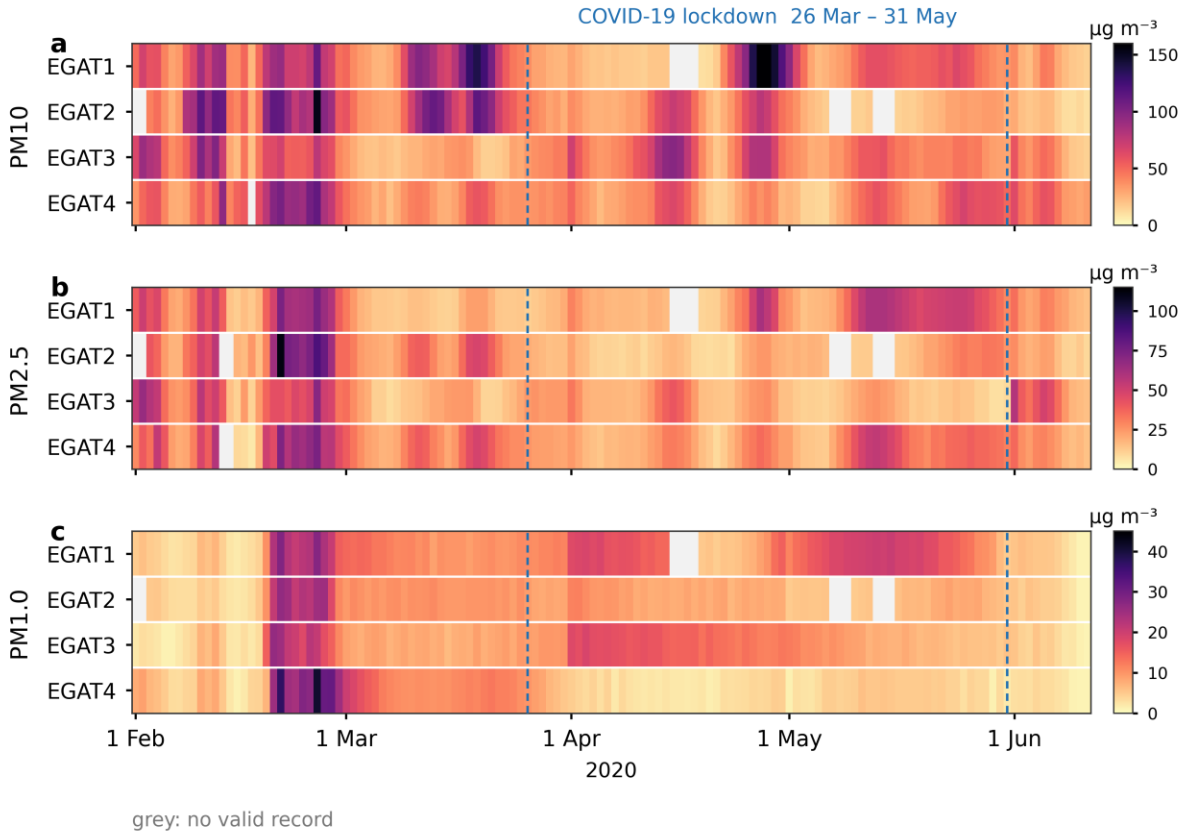


Fig. 13 The complete 24-h record by station and day, with concentration mapped to colour: a PM10, b PM2.5, c PM1.0. Each block has one row per station and one column per day. Grey marks a day with no valid record at that station. The dashed lines mark the start and end of the nationwide COVID-19 lockdown and curfew

Because the four units are of one design and sample the same regional air mass at points a few hundred metres apart, the extent to which they agree can be measured directly, and that measurement is reported here in place of the assumption that co-deployed units of one design behave alike. Bland-Altman analysis of the six station pairs, expressed as the ratio between two stations because the concentrations are approximately log-normal, gives 95% limits of agreement of 0.35 to 3.26 for PM10 and 0.33 to 2.83 for PM2.5 (Fig. 14a, b): one station may read between about a third and about three times another on the same day. Where that disagreement comes from is shown by the decomposition that follows. A two-way random-effects decomposition of the log-transformed 24-h concentrations, on the 118 to 120 days for which all four stations reported, partitions the total variance into a between-day component, a between-station component, and a day-by-station residual (Fig. 14c). The between-day component accounts for 42.2% (PM10), 50.9% (PM2.5), and 56.4% (PM1.0) of the total. The between-station component, which represents a fixed offset of one station relative to another, is small and grows as particle size falls: 0.7% for PM10, 4.1% for PM2.5, and 10.5% for PM1.0. After adjustment for autocorrelation, which reduces the effective number of days from about 120 to between 4 and 11, the offset remains statistically detectable for the two finer fractions ($F = 11.6$, $p < 0.001$ for PM2.5; $F = 39.0$, $p < 0.001$ for PM1.0) but not for PM10 ($F = 2.5$, $p = 0.082$).

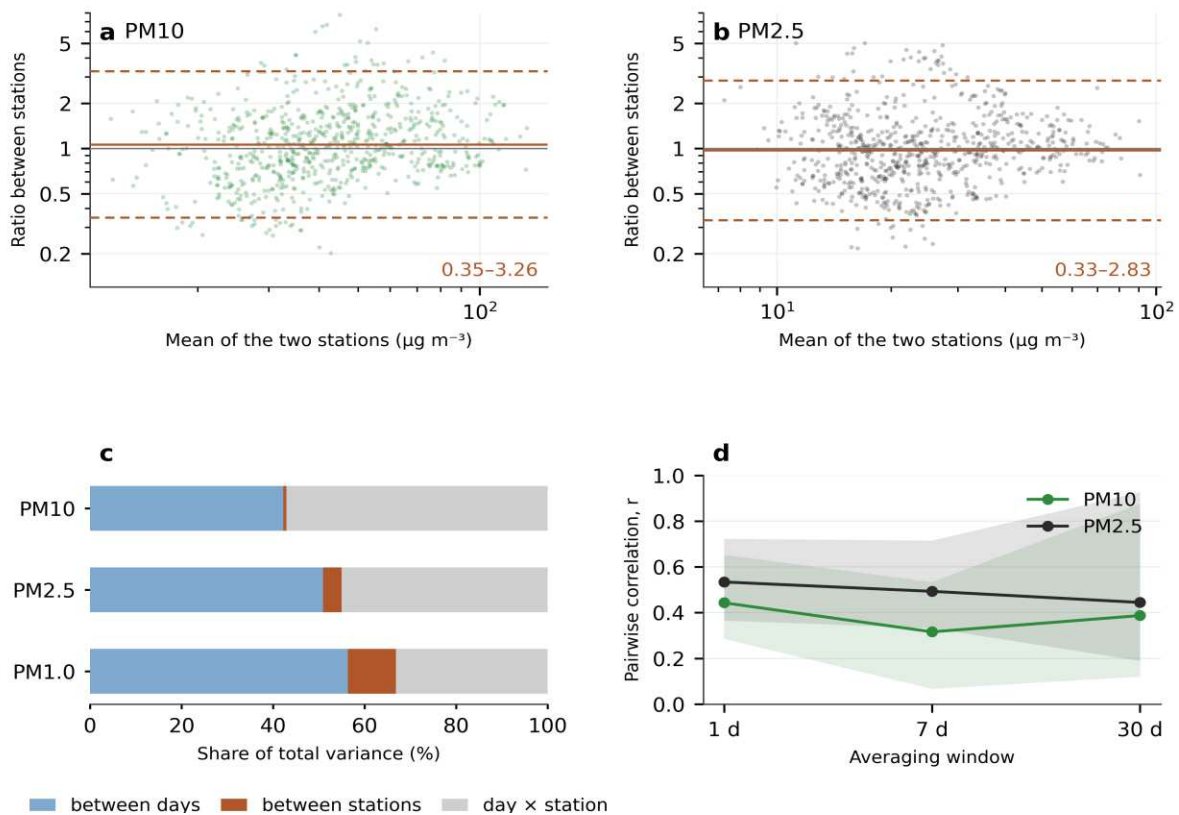


Fig. 14 Agreement between the four co-deployed units over the 132-day campaign. a Bland-Altman plot for PM10, pooling all six station pairs, plotted as the ratio between two stations against their mean; the solid line is the mean ratio and the dashed lines the 95% limits of agreement, whose values are printed in the panel. b The same for PM2.5. c Share of the total variance of the log-transformed 24-h concentrations attributable to differences between days, to fixed differences between stations, and to the day-by-station interaction. d Mean pairwise correlation between stations against the averaging window, with the range over the six pairs shaded

The same decomposition gives the intraclass correlation coefficient, which expresses how far a measurement can be relied upon as a description of the site rather than of the unit that made it. For a single unit, ICC(A,1) is 0.42 for PM10 (95% CI 0.32 to 0.51), 0.51 for PM2.5 (0.39 to 0.60), and 0.56 for PM1.0 (0.42 to 0.67), which falls in the range conventionally described as poor to moderate. For the mean of all four units, ICC(A,k) rises to 0.75, 0.81, and 0.84 respectively, in the moderate to good range. A single unit of this design is therefore a weak estimate of the site concentration on a given day, while the four-unit mean is a usable one.

The remaining variance, 57.1% for PM10, 45.0% for PM2.5, and 33.1% for PM1.0, is the day-by-station interaction. It is the largest single component for PM10 and represents disagreement between stations that changes from day to day rather than a fixed offset. Pairwise correlation over the six station pairs confirms this. On the 118 to 132 paired days available, r ranged from 0.285 to 0.653 for PM10 and from 0.366 to 0.724 for PM2.5 (Table 4, shown graphically in Fig. 15). Once the autocorrelation of the daily series is taken into account, none of the six PM10 correlations is distinguishable from zero ($p = 0.20$ to 0.48) and only two of the six for PM2.5 are (EGAT1 against EGAT4, $p = 0.017$; EGAT2 against EGAT4, $p = 0.012$). The Deming slopes tell the same story: for PM10 they

range from 0.38 to 1.00, so four of the six pairs depart substantially from the proportional agreement that co-located units of one design would be expected to show.

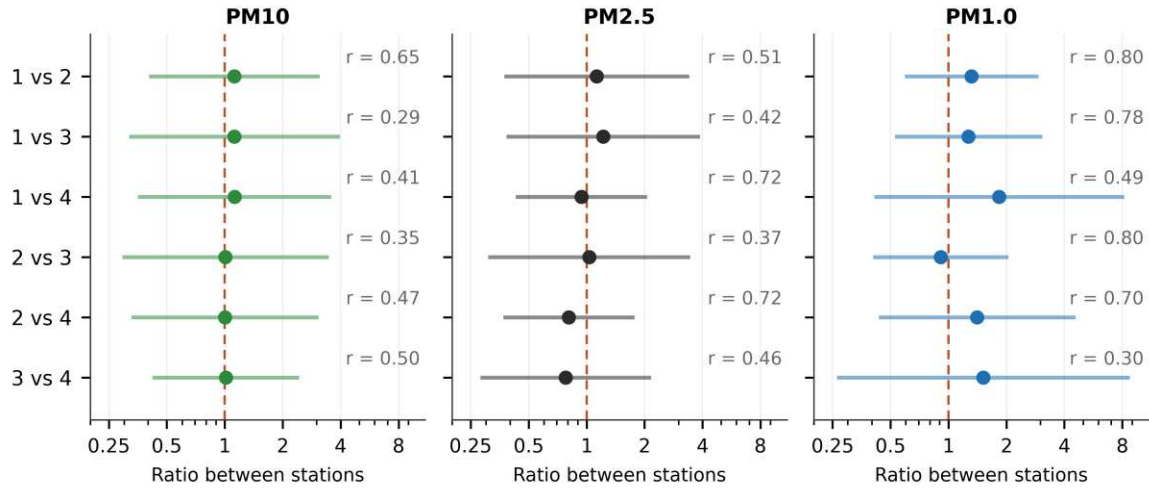


Fig. 15 Agreement between each pair of the four units, from the log-transformed 24-h averages. Points are the mean ratio of the first station to the second and bars are the 95% limits of agreement; the dashed line marks equality. The Pearson correlation of the log concentrations is printed beside each pair. Between 118 and 132 paired days were available for each combination

Table 4 Agreement between each pair of the four units over the campaign, from the log-transformed 24-h averages, shown graphically in Fig. 15. Pairs are identified by station number, so 1 vs 2 is EGAT1 against EGAT2

Fraction	Pair	n	n eff	r (95% CI)	p	Deming slope	Ratio (95% limits)
PM10	1 vs 2	120	6	0.653 (-0.42–0.96)	0.211	1.00	1.12 (0.40–3.11)
	1 vs 3	128	9	0.285 (-0.47–0.80)	0.475	0.38	1.12 (0.32–3.96)
	1 vs 4	127	7	0.406 (-0.51–0.89)	0.398	0.48	1.12 (0.35–3.56)
	2 vs 3	124	8	0.351 (-0.47–0.85)	0.412	0.45	1.01 (0.29–3.46)
	2 vs 4	123	7	0.468 (-0.44–0.90)	0.310	0.50	1.00 (0.33–3.07)
	3 vs 4	131	9	0.495 (-0.28–0.88)	0.202	0.94	1.01 (0.42–2.43)
PM2.5	1 vs 2	118	7	0.508 (-0.44–0.92)	0.289	1.02	1.13 (0.37–3.41)
	1 vs 3	128	9	0.421 (-0.35–0.85)	0.281	0.83	1.22 (0.38–3.88)
	1 vs 4	126	10	0.723 (0.16–0.93)	0.017	0.80	0.94 (0.43–2.06)
	2 vs 3	122	10	0.366 (-0.33–0.81)	0.304	0.77	1.03 (0.31–3.45)
	2 vs 4	122	10	0.724 (0.20–0.93)	0.012	0.79	0.81 (0.37–1.77)
	3 vs 4	130	13	0.465 (-0.11–0.81)	0.106	0.82	0.78 (0.28–2.16)
PM1.0	1 vs 2	120	4	0.804 (-0.69–1.00)	0.267	0.79	1.32 (0.59–2.93)

Fraction	Pair	n	n eff	r (95% CI)	p	Deming slope	Ratio (95% limits)
	1 vs 3	128	4	0.783 (-0.53–0.99)	0.211	1.00	1.27 (0.53–3.07)
	1 vs 4	128	5	0.491 (-0.73–0.96)	0.475	1.42	1.84 (0.41–8.19)
	2 vs 3	124	4	0.798 (-0.54–0.99)	0.208	1.29	0.91 (0.41–2.05)
	2 vs 4	124	5	0.701 (-0.60–0.98)	0.275	1.77	1.41 (0.43–4.57)
	3 vs 4	132	5	0.299 (-0.77–0.93)	0.649	1.79	1.52 (0.26–8.72)

n is the number of paired days; n_eff is the effective sample size after adjustment for the lag-1 autocorrelation of each series. The confidence interval and p value for r are computed on n_eff, not on n, so they are wider and larger than an unadjusted calculation would give.

The Deming slope is the errors-in-variables regression of the second station on the first, appropriate here because neither station is a reference and both carry measurement error. A slope of 1.00 indicates proportional agreement.

The ratio is the mean of the first station divided by the second. A ratio of 1.00 indicates no systematic difference. Limits of agreement spanning, for example, 0.35 to 3.26 mean that on 95% of days one station reads between 0.35 and 3.26 times the other.

Two checks bear on the origin of that disagreement. First, it does not diminish when the records are averaged over longer windows: the mean pairwise correlation for PM10 is 0.44 at 1 day, 0.32 at 7 days, and 0.39 at 30 days, and for PM2.5 it is 0.53, 0.49, and 0.44 respectively (Fig. 14d). Independent measurement noise would average out and the correlation would rise; it does not. The adjustment for autocorrelation is deliberately conservative, and for PM1.0, whose daily series is the most persistent of the three, it leaves an effective sample of only four or five days, so the PM1.0 correlations in Table 4 are reported with intervals too wide to be informative rather than as evidence of disagreement. Second, the effect is not confined to one faulty unit. The mean correlation of each station with the other three lies between 0.38 and 0.46 for PM10 and between 0.42 and 0.64 for PM2.5, so no station stands apart as the source of the disagreement.

Weekday and weekend concentrations

If concentrations at the site were driven mainly by activity within the plant and its immediate surroundings, a weekday-weekend contrast would be expected. Taking the four-station daily mean as a single series, weekday concentrations exceeded weekend concentrations by 6.5% for PM10 (49.4 against 46.4 $\mu\text{g}/\text{m}^3$), 7.7% for PM2.5 (28.8 against 26.7 $\mu\text{g}/\text{m}^3$), and 5.5% for PM1.0 (9.5 against 9.0 $\mu\text{g}/\text{m}^3$), none of which is statistically distinguishable from no difference (Mann-Whitney U, $p = 0.84$, 0.50, and 0.66 respectively; 94 weekdays and 38 weekend days). The record therefore gives no evidence of a weekly activity cycle at the site.

Comparison with the government reference station

Comparison with the nearby PCD16 government reference station showed broadly consistent temporal trends in PM10 and PM2.5 across the four plant stations (Fig. 16). The available comparison covers an 8-day window, from 26 January to 2 February 2020, rather than the full 132-day record; six of those eight days fall in the commissioning period that precedes the analysed record, and only 1 and 2 February lie within it. It is qualitative, and no quantitative correlation coefficient between the prototype stations and PCD16 was computed for this deployment.

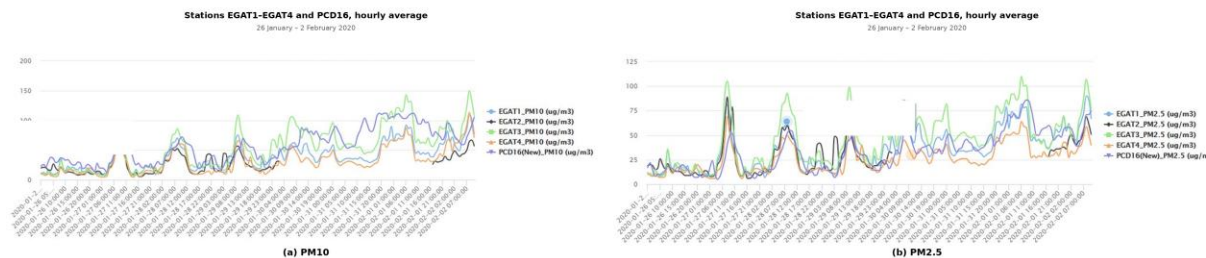


Fig. 16 Comparison of a PM10 and b PM2.5 concentrations measured across the four power-plant stations with the nearby Thailand Pollution Control Department reference station (PCD16), for an 8-day comparison window from 26 January to 2 February 2020, spanning the commissioning period and the first two days of the 132-day record analysed here

Discussion

Evaluation of the study hypothesis

The hypothesis set out in the Introduction was supported in part. The charging, impaction, and Faraday-cup detection chain transferred to the PM10/PM2.5/PM1.0 configuration without modification to the charging or detection stages, and the four units operated unattended in an active power-plant environment for 132 days at 92% to 100% daily data recovery, which is the operational half of the hypothesis. The measurement half is only partly supported: the four stations resolved a common temporal pattern and tracked the nearby government reference station in trend, but that comparison covers 8 days, six of them before the analysed record begins, rather than the campaign, and was not quantified, and the PM1.0 channel that distinguishes this configuration was never verified against a size-selective reference. The platform is therefore demonstrated as a multi-point continuous area monitor and not yet as a verified PM1.0 instrument.

Status of the reconfigured PM1.0 channel

Because no dedicated cut-point verification was obtained for the reconfigured third stage, the PM1.0 channel is regarded here as provisionally configured rather than independently verified. The PM1.0 concentrations reported above should accordingly be read as indicative of the sub-micron fraction rather than as a metrologically established PM1.0 measurement, and dedicated cut-point verification is a priority before these data are used to support filter-loading decisions.

Interpretation of the field record

The mean PM2.5/PM10 ratio of 53.2–68.6% indicates that fine particles constitute a substantial share of total PM10 mass at this site, consistent with a combustion-influenced source profile. The decline from February toward May and June coincides with the end of the seasonal agricultural and forest-burning haze period characteristic of the dry season in Thailand (Moran et al., 2019). The decline is not uniform across fractions: PM10 and PM1.0 fall monotonically from March to June, whereas PM2.5 reaches a minimum in April and rises again in May (Fig. 6), so PM10 and PM1.0 track the seasonal transition more closely than PM2.5 does. Month-to-month data recovery is high

and approximately even across the record (Fig. 6), so the identification of February as the dominant month does not rest on differential data loss: February, March, April, and May each contributed a complete or near-complete set of four-station daily means, and only June, truncated at 11 days by the planned end of the campaign, is under-represented. The station means and standard deviations, and the monthly means, in Fig. 6 allow the spread behind each reported average to be judged.

Interpretation of the apparent differences between stations is similarly constrained. Inter-station differences such as the highest 24-h PM₁₀ average of 160.8 $\mu\text{g}/\text{m}^3$ at EGAT1 against 101.2 $\mu\text{g}/\text{m}^3$ at EGAT3 (Fig. 6) can now be assessed against the agreement analysis rather than left open. The four stations occupy distinct settings within the site (Fig. 5), from the enclosed surroundings of the combined-cycle unit to open ground at the substation, so some real spatial structure is plausible. The agreement analysis, however, points away from that explanation as the principal one. Fixed between-station differences account for only 0.7% of the variance in PM₁₀ and 4.1% in PM_{2.5}, whereas the day-by-station interaction accounts for 57.1% and 45.0%. Real spatial structure driven by nearby sources would be expected to produce a persistent ranking of the stations, that is, a large fixed component; what is observed instead is disagreement that changes from day to day. Two further observations point the same way. The disagreement does not diminish under temporal averaging, as independent measurement noise would, and it is not concentrated in any one unit. Taken together these indicate that the dominant contribution is time-varying, unit-specific behaviour of the instruments rather than micro-scale spatial variation in the aerosol. Subject to these constraints, the continuously logged, simultaneous four-station records provide a practical starting point for relating ambient PM levels around the plant to inlet-filter loading trends, although the present study stops short of demonstrating that link directly.

Comparison with air quality standards and guidelines

The station-mean concentrations of 44.9–54.1 $\mu\text{g}/\text{m}^3$ (PM₁₀) and 24.8–30.8 $\mu\text{g}/\text{m}^3$ (PM_{2.5}) are set against health-based reference values here for context only. Because the campaign spans 132 days rather than a calendar year, the comparison is indicative and is not an assessment of compliance with any standard.

During the campaign the Thai ambient air quality standards were 120 $\mu\text{g}/\text{m}^3$ (24 h) and 50 $\mu\text{g}/\text{m}^3$ (annual) for PM₁₀ (NEB, 2004), and 50 $\mu\text{g}/\text{m}^3$ (24 h) and 25 $\mu\text{g}/\text{m}^3$ (annual) for PM_{2.5} (NEB, 2010). The PM_{2.5} values were subsequently tightened by notification of the National Environment Board (NEB) of Thailand: the annual value to 15 $\mu\text{g}/\text{m}^3$ with effect from 9 July 2022, and the 24-h value to 37.5 $\mu\text{g}/\text{m}^3$ with effect from 1 June 2023, the 24-h value of 50 $\mu\text{g}/\text{m}^3$ remaining in force until 31 May 2023 (NEB, 2022). On that basis the station-mean PM₁₀ concentration at EGAT1 (54.1 $\mu\text{g}/\text{m}^3$) exceeds the annual PM₁₀ value of 50 $\mu\text{g}/\text{m}^3$ then in force, while the other three stations fall below it, and the station-mean PM_{2.5} concentration exceeds the annual PM_{2.5} value of 25 $\mu\text{g}/\text{m}^3$ then in force at three of the four stations, the fourth (EGAT3, 24.8 $\mu\text{g}/\text{m}^3$) falling marginally below it. All four station means are 1.7 to 2.1 times the annual PM_{2.5} value now applicable. Against the WHO air quality guidelines, which set annual values of 15 $\mu\text{g}/\text{m}^3$ for PM₁₀ and 5 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and 24-h values of 45 and 15 $\mu\text{g}/\text{m}^3$ respectively (WHO, 2021), the recorded means exceed the PM₁₀ guideline by factors of 3.0 to 3.6 and the PM_{2.5} guideline by factors of 5.0 to 6.2.

One qualification applies. The comparison rests on ambient concentrations at four in-plant points, which are not equivalent to the fixed-site, siting-controlled measurements on which regulatory determinations are based.

Relevance to occupational and environmental hygiene

The concentrations recorded are roughly two orders of magnitude below the general workplace limits applied to particulates not otherwise specified. The American Conference of Governmental Industrial Hygienists recommends, for that category, 8-h time-weighted average threshold limit values of 3 mg/m³ for the respirable fraction and 10 mg/m³ for the inhalable fraction (ACGIH, 2024), against station means of 0.045 to 0.054 mg/m³ for PM₁₀; the results therefore do not indicate an occupational dust hazard of the kind those limits were written to control. The hygiene relevance of the record lies elsewhere. The four stations characterise, continuously and at four points, the ambient environment in which plant personnel work, over a period that included the seasonal haze maximum; and the concentrations recorded are of the same order as the working-day exposures measured for outdoor workers elsewhere in the Bangkok Metropolitan Region (Archer et al., 2024). On 119 of the 132 days of the campaign the four-station daily mean PM_{2.5} exceeded the WHO 24-h guideline value, and on 24 days it exceeded the Thai 24-h value now in force, so a worker on outdoor duty would have spent most of the campaign in air above health-based guideline levels even though no occupational limit was approached.

For a facility in a region with a pronounced annual haze season, a permanently installed multi-point monitor of this kind supplies the continuous record needed to identify the periods in which outdoor and semi-enclosed work contributes materially to personal exposure, and to time work scheduling, shelter, or respiratory protection accordingly. That record also resolves a sub-micron fraction that neither ambient standards nor mass-based occupational limits address by size. The present deployment demonstrates the measurement capability rather than any exposure-control decision derived from it; no personal sampling was performed, and no worker location, task, or shift information was collected, so no exposure assessment is offered here.

Comparison with gas-turbine emission and regional PM studies

Because the present study measures ambient air within the plant boundary rather than stack emissions, the recorded concentrations reflect the surrounding regional air mass rather than the combustion products of the plant itself, which are released from an elevated stack physically separated from the air intake. The comparison that follows, against independently reported combustion-source and regional air-quality data, is offered as a plausibility check and a hypothesis for future site-specific testing, not as a demonstrated source attribution: no source-apportionment or meteorological analysis was performed on the present four-station dataset itself.

Stack emission comparison

Natural-gas combustion is well documented to produce markedly less particulate matter than coal or oil combustion. In a direct comparison of stack filterable PM concentrations from operating power plants, liquefied natural gas (LNG)-fired gas turbines were reported at approximately 0.05 mg/m³, compared with 1.86 mg/m³ for bituminous coal-fired units and 3.05 mg/m³ for oil-fired units, roughly two orders of magnitude lower than coal (Yu et al.,

2021). Separately, stack total PM, PM₁₀, and PM_{2.5} concentrations measured directly at 14 LNG-fired gas-turbine sites averaged 51.8, 38.5, and 28.1 µg/m³, respectively (Kim et al., 2021). The station-mean ambient PM₁₀ (44.9–54.1 µg/m³) and PM_{2.5} (24.8–30.8 µg/m³) concentrations recorded in the present study fall in a broadly similar numerical range to these reported gas-turbine stack concentrations (Kim et al., 2021), despite measuring a physically distinct air stream, namely ambient intake air rather than combustion exhaust. This is a comparison of magnitude between unrelated measurements at different facilities and should be read as weak, indirect evidence only: at most, it is not inconsistent with natural-gas combustion contributing relatively little to the ambient PM burden at this plant, but it does not by itself demonstrate this, since a numerical coincidence of this kind could also arise for unrelated reasons.

Regional source apportionment and meteorology

A second, independent line of evidence comes from regional source-apportionment and climatological studies conducted in Samut Prakan Province, the same province as the present deployment. An analysis of 2018–2021 PM_{2.5} data from the PCD network in Samut Prakan reported a monthly mean of 44 ± 26 µg/m³ in January, exceeding the provincial annual average by 83%, with a recorded daily peak of 114 µg/m³. That study attributed the pronounced winter peak to reduced atmospheric ventilation, namely lower planetary boundary layer height and wind speed, rather than to a change in emission rate, since anthropogenic PM_{2.5} emissions in the province showed little month-to-month variation (Vongruang et al., 2024). The same study cites an earlier source-apportionment analysis attributing more than 60% of fine PM in Samut Prakan to boiler combustion sources generally, not specific to any one facility, and about 10% to biomass burning, while a separate apportionment for the wider Bangkok Metropolitan Region attributed only about 11% of PM_{2.5} to industrial sources including power plants collectively, compared with 44% from vehicles and 24% from biomass burning (Vongruang et al., 2024).

The seasonal pattern reported for Samut Prakan generally, namely a winter and dry-season peak driven by meteorology rather than emissions, and the station-mean and maximum PM_{2.5} concentrations recorded in the present study (24.8–30.8 µg/m³ station mean; 70–111 µg/m³ highest 24-h average) are broadly consistent with each other. This provincial picture is reinforced by the immediate setting of the plant itself: as noted under Materials and methods, the site lies within a mixed community and industrial area, with residential neighbourhoods and other industrial facilities in the immediate vicinity, so nearby community-related and industry-related emissions, in addition to the area-wide sources discussed above, are a plausible contributor to the concentrations recorded at the four stations. Taken with the stack-concentration comparison above, this is compatible with the hypothesis that concentrations at the four stations are shaped at least in part by regional meteorology, nearby community and industrial activity, and area-wide emission sources, rather than solely by the natural-gas combustion of the plant itself. It does not establish that hypothesis. Direct testing at the plant, for example through source apportionment or spatial mapping of nearby emission sources, is identified below as a priority for future work.

Confounding by COVID-19 restrictions

The 132-day campaign coincided with the first wave of COVID-19 restrictions in Thailand. Partial restrictions took effect on 22 March 2020 (Dejchanchaiwong & Tekasakul, 2021) and a nationwide lockdown and curfew were in force from 26 March to 31 May 2020 (Wetchayont, 2021), so the interval from 26 March to 31 May, amounting to 67 of the 132 days of the deployment, fell within a period of substantially reduced traffic, commercial, and industrial activity across the Bangkok Metropolitan Region. That period overlaps the decline in concentrations reported above and is a confounder for the seasonal interpretation offered for it.

Published assessments for Greater Bangkok indicate that the effect was appreciable but not uniform. Comparing the lockdown period with the corresponding period of 2019, one analysis reported reductions of 15.8% in PM_{2.5} and 31.7% in PM₁₀ (Wetchayont, 2021), whereas a comparison of April 2020 with April 2019 found an 11.1% reduction at roadside sites but an increase of 16.7% at business-area sites, with no clear relationship between the PM_{2.5} change and the measured reductions in traffic volume and diesel consumption (Dejchanchaiwong & Tekasakul, 2021). Source apportionment carried out in Samut Prakan during the same period identified traffic as the largest single contributor to PM_{2.5} in that province (Amphalop et al., 2023), which is the source category most directly reduced by the restrictions.

The present dataset cannot separate the meteorological transition from the restriction effect. No equivalent measurements were made at the same four stations in a year without restrictions, and no traffic, activity, or meteorological covariates were recorded alongside the PM data. The decline from February toward May and June should therefore be read as the combined result of the dry-to-wet-season transition and the COVID-19 restrictions in unknown proportion, rather than as a seasonal signal alone. The monthly means now available bear on this. April fell entirely within the lockdown and carries the lowest monthly PM_{2.5} of the record (20.9 µg/m³), but May, also entirely within the lockdown, is higher (28.3 µg/m³) than both April and March. A restriction effect operating alone would not produce a rise in the middle of the restricted period, so meteorology evidently continues to act on the fine fraction throughout; the two influences remain inseparable in this dataset, but neither can be treated as dominant on the evidence available.

Implications for multi-point deployment

The reproducibility result carries a practical consequence for the deployment of this class of instrument. Limits of agreement spanning roughly a threefold range in either direction mean that a concentration difference between two of these stations on a given day cannot be interpreted as a real difference in the air at those two points unless it is large. Comparisons that rest on the pooled record, such as the site-mean time series, the monthly means, and the counts of days above a threshold, are unaffected, because averaging over four units and many days suppresses the day-by-station term; this is what the rise in the intraclass correlation from 0.42 for a single unit to 0.75 for the four-unit mean expresses in one number. Comparisons between individual stations are not supported by the present data.

The result also sets a requirement for future deployments of the platform rather than condemning it. Agreement was measured here after the fact, from units that had never been compared against one another, in a field campaign that included no scheduled cross-checks. A side-by-side co-location period before dispersal, a repeat co-location at the

close of the campaign, and a periodic return of one unit to a common reference point would identify unit-specific drift while it is happening and allow it to be corrected. The measurements needed to do that are the ones listed under Recommendations.

Limitations of the study

Several limitations of the present study should be noted and addressed before the results are relied upon for filter-maintenance or air-quality decision-making. They are listed roughly in order of severity, with the first three considered the highest priority to close before the instrument or its data are used for regulatory or maintenance decisions.

First, and most importantly, no reference-instrument comparison was conducted for the specific PM₁₀/PM_{2.5}/PM_{1.0} configuration or at the power-plant deployment site. The correlation coefficients cited under Materials and methods (Yawootti et al., 2015b; Intra et al., 2016, 2018b) were obtained at a different site, at a different time, and, for the PM_{1.0} channel, with a different (photometric, non-impaction) reference measurement, so their applicability to the present configuration and site is inferred rather than demonstrated.

Second, the PM_{1.0} impactor stage was reconfigured from the earlier TSP design without an unambiguous, independently documented nozzle geometry or a dedicated cut-point verification for this deployment; the reported $\approx 1.03 \mu\text{m}$ cut-point should be confirmed against the as-built hardware and, ideally, verified experimentally following the same procedure used for the PM₁₀ and PM_{2.5} stages (Intra, 2018).

Third, unit-to-unit agreement was quantified after the fact from the deployed records rather than established by design, since no side-by-side co-location of the four units at a single point was carried out either before deployment or during the campaign; the agreement statistics reported here describe how the units behaved in the field but carry no independent reference against which either instrumental drift or real spatial variation could be judged. Every prior study in the lineage of this platform (Table 1), including the earlier coal-mine study (Intra, 2018), describes a single deployed unit; the present study is the first to field multiple units at once, but no co-location or cross-calibration of two or more of the four units, either before deployment or during the 132-day campaign, was carried out. Apparent inter-station differences therefore cannot be attributed with confidence to real spatial variation within the plant.

Fourth, as with the earlier coal-mine deployment (Intra, 2018), no dedicated vibration or mechanical-shock qualification testing was performed for the power-plant environment, and no field zero and span calibration and drift-correction protocol specific to this deployment was documented.

Fifth, 205 station-hours (1.7% of the raw record) failed the physical-consistency criterion $\text{PM}_{1.0} \leq \text{PM}_{2.5} \leq \text{PM}_{10}$ and were retained and corrected, rather than discarded, before analysis. The correction restores an ordering that must hold physically, but it does not recover the true PM₁₀ values over the affected periods, so the EGAT₂, EGAT₃, and EGAT₄ statistics for the affected days in February carry an additional uncertainty that is not reflected in the standard deviations in Fig. 6.

Sixth, the comparison with the PCD16 government reference station is qualitative only, and covers an 8-day window (26 January to 2 February 2020), six days of which fall in the commissioning period before the analysed record begins, rather than the 132-day record; no paired correlation statistic, averaging-time alignment, or distance and siting adjustment between PCD16 and the four in-plant stations was computed.

Seventh, periodic maintenance, comprising cleaning of the impaction plates, ion-trap electrodes, and Faraday-cup filters to remove particulate build-up from continuous operation, was carried out during the present deployment, consistent with the servicing needs reported for the earlier coal-mine study (Intra, 2018); unlike that study, however, a documented servicing schedule and specific maintenance dates were not recorded, so although overall data recovery is known (Fig. 6), individual outages cannot be traced to particular servicing events.

Eighth, the deployment ran for 132 days (1 February to 11 June 2020), capturing a single dry-to-wet-season transition rather than a full annual cycle, and its final calendar month is represented by only the 11 days preceding the planned close of the campaign; the extent to which the reported concentrations and ratios generalise to other seasons, or to other combined-cycle plants, has not been established. The period also coincided with the first wave of COVID-19 restrictions in Thailand, so the decline in concentrations over the campaign cannot be attributed to the seasonal transition alone (see Discussion).

Ninth, the statistics reported here were computed directly from the logged measurement record, with a data recovery of 92% to 100%. They nonetheless remain single-instrument measurements with no co-located reference at this site, so internal consistency should not be read as external accuracy. The alignment of the 24-h averaging window with the local calendar day was not verified against the logger clock, so the daily averages may be offset from the midnight-to-midnight day on which the Thai and WHO 24-h values are defined, and the exceedance counts in Fig. 6 inherit that offset.

Tenth, no direct, paired measurement of gas-turbine inlet-filter differential pressure alongside the PM concentration data was available for this study; consequently, the motivating rationale set out in the Introduction rests on published turbomachinery findings (Büyükköse & Aslan, 2026) rather than on any filter-pressure data collected at this plant.

Eleventh, as previously noted for the earlier study (Intra, 2018), correlation and regression describe association rather than agreement between two methods, so the reference-instrument statistics reproduced in Fig. 3 do not by themselves establish that the electrostatic monitor is interchangeable with reference methods.

Finally, the comparison drawn under Discussion against gas-turbine stack emission data (Yu et al., 2021; Kim et al., 2021), regional Samut Prakan climatology (Vongruang et al., 2024), and the mixed community and industrial setting of the plant is indirect: no source-apportionment or meteorological analysis was performed on the present dataset itself, and no survey or mapping of specific nearby emission sources was conducted. The inference that regional, local, and meteorological factors, rather than the combustion of the plant itself, dominate the recorded concentrations is therefore a plausibility argument based on published literature and general site context rather than a finding demonstrated directly from the four-station data.

Recommendations

The following measures are recommended before the data reported here are used to inform gas-turbine inlet-filter maintenance or air-quality decisions. First, a co-located comparison against reference and equivalent-method instruments should be conducted at, or as close as practicable to, the power-plant site, covering all three size fractions of the present configuration. Second, the PM_{1.0} stage cut-point should be confirmed against the as-built hardware and verified experimentally, for example by a co-located challenge with monodisperse polystyrene latex particles bracketing 1 μm (0.5, 0.7, 1.0, and 1.5 μm), or by parallel comparison against a scanning mobility particle sizer or optical particle counter spanning the same size range, before the PM_{1.0} channel is used for regulatory or maintenance purposes.

Third, all deployed units should be compared side by side at a common location before or after deployment, so that inter-station differences can be separated from unit-to-unit calibration differences. Fourth, a documented servicing schedule, maintenance log, and quantitative data-completeness record should be maintained for future long-term deployments of this platform, together with a field zero and span calibration and drift-correction protocol. Fifth, agreement between the electrostatic monitor and reference methods should be assessed by Bland–Altman analysis of the raw paired observations (Bland & Altman, 1986), in addition to correlation and regression, before the instrument is treated as interchangeable with reference methods.

Sixth, gas-turbine inlet-filter differential pressure should be logged alongside the PM concentration data at the same site, so that the operational rationale for the deployment can be tested directly. Seventh, a source-apportionment or ventilation-index analysis of the four-station dataset, together with a survey of specific nearby emission sources, should be undertaken to test the interpretation offered under Discussion. Eighth, the 205 station-hours that failed the physical-consistency criterion should be diagnosed against the raw electrometer signal for the affected channels, and both checks applied automatically in future deployments so that out-of-range readings and channel offsets are caught in the field rather than in post-processing. Ninth, the area record should be paired with task-based personal sampling for the outdoor and semi-enclosed job categories at the plant, so that the relationship between fixed-point area concentration and personal exposure can be established rather than assumed, and so that an exceedance of a health-based guideline value at a station can be translated into an action for the workforce, such as rescheduling outdoor tasks or issuing respiratory protection. Finally, the deployment should be extended to a full annual cycle, in a year without pandemic-related activity restrictions, so that the reported concentrations and ratios can be generalised beyond a single dry-to-wet-season transition.

Conclusions

A three-channel electrostatic mass monitor, previously validated for TSP, PM₁₀, and PM_{2.5} monitoring at a deep open-pit lignite mine, was adapted to a PM₁₀/PM_{2.5}/PM_{1.0} configuration and deployed as four simultaneous units for 132 days at a combined-cycle power plant in Samut Prakan Province, Thailand. The adaptation reused the validated corona-charging, inertial-impaction, and Faraday-cup measurement principle without modification for the PM₁₀ and PM_{2.5} channels, and reconfigured the third channel from an unclassified TSP inlet to a PM_{1.0} impaction

stage, although cut-point verification for that stage remains provisional pending confirmation of the as-built nozzle geometry.

The 132-day, four-station deployment recorded station-mean concentrations of 44.9–54.1 $\mu\text{g}/\text{m}^3$ (PM₁₀), 24.8–30.8 $\mu\text{g}/\text{m}^3$ (PM_{2.5}), and 7.5–11.9 $\mu\text{g}/\text{m}^3$ (PM_{1.0}), with mean PM_{2.5}/PM₁₀, PM_{1.0}/PM_{2.5}, and PM_{1.0}/PM₁₀ ratios of approximately 53–69%, 24–39%, and 17–22%, and a seasonal pattern consistent with the regional dry-season haze period, although the campaign coincided with COVID-19 activity restrictions that confound this interpretation. At the level of the motivation set out in the Introduction, the deployment demonstrates that a single electrostatic platform can deliver continuous, simultaneous, multi-point, three-fraction PM data, of the kind needed to characterise the particulate loading reaching gas-turbine air-inlet filters, a measurement that conventional single-fraction reference instrumentation could supply only by operating one instrument per fraction at each point, and that the agreement between co-deployed units of that platform must be measured rather than assumed. No cost comparison was made in this study, so the economic case for the approach is not quantified here. In a plant setting the same record also characterises the ambient environment in which personnel work, at a size resolution that neither ambient standards nor mass-based occupational limits address. This extends the validated instrument platform from the single-unit, occupational-exposure deployment of the earlier coal-mine study to multi-point area monitoring at a fixed industrial site. Several validation gaps identified under Limitations of the study, most notably the absence of a site-specific and configuration-specific reference-instrument comparison, of PM_{1.0}-stage cut-point verification, of unit-to-unit reproducibility testing across the four simultaneously deployed instruments, and of a direct link between the recorded PM data and measured filter differential pressure, should be closed before the results are relied upon for filter-maintenance decision-making. Future work should therefore proceed in three steps: a co-located reference comparison and PM_{1.0} cut-point verification at the deployment site; side-by-side operation of the four units to establish reproducibility; and a full annual campaign paired with filter differential-pressure logging and task-based personal sampling, so that the area record can be related both to plant operation and to worker exposure.

Declarations

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Competing interests The Electricity Generating Authority of Thailand, which funded this work, owns and operates the South Bangkok combined-cycle power plant at which the instruments were deployed. The funder has authorised publication of the material presented in this paper but not of the wider project record, which remains its property. No result reported here depends on any document that is not publicly available. The author has no other relevant financial or non-financial interests to disclose.

Ethics approval Not applicable. This study did not involve human participants, their data or biological material, or animals.

Consent to participate Not applicable.

Consent to publish Not applicable.

Data availability All data underlying the findings of this study are contained within the article. The complete 24-h average PM₁₀, PM_{2.5}, and PM_{1.0} record for every station and every day of the campaign is plotted in Figs. 7 to 12, and the corresponding station and monthly summary statistics, with standard deviations and daily counts, are given in Fig. 6. The raw electronic record was generated under a research contract with the Electricity Generating Authority of Thailand and is the property of the funder, which has authorised publication of the material presented here but not of the record as a whole, so it cannot be deposited in a public repository. Requests for further access are directed to the corresponding author.

Author contributions Panich Intra conceived and designed the study, adapted and deployed the instruments, analysed the data, and wrote the manuscript.

Ethical responsibilities of authors All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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