

Commentary

From Complaint-Driven Response to Preventive Management: Strengthening Indoor Air Quality Management in Malaysian Buildings

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Indoor air quality (IAQ) represents an important component of occupational and environmental health because conditions within buildings are determined by complex interactions among ventilation, occupancy, indoor pollutant sources, outdoor air quality, temperature, humidity, building materials, mechanical systems and maintenance practices. Malaysia has an established workplace framework through the *Industry Code of Practice on Indoor Air Quality 2010* (ICOP IAQ 2010), which provides criteria for selected physical, chemical and biological parameters and establishes procedures for IAQ investigation, assessment and control. Although the existing framework incorporates preventive elements, contemporary evidence supports a stronger emphasis on prevention as a routine component of building management rather than relying on formal complaints as the principal trigger for identifying IAQ deficiencies. This commentary examines the central but non-exclusive role of ventilation, the appropriate interpretation of carbon dioxide (CO₂), the growing importance of particulate matter and outdoor-to-indoor pollutant transport, and the particular difficulties created by Malaysia's hot and humid climate. Recent evidence from Malaysian offices, hospitals and educational environments demonstrates that occupant density, ventilation characteristics, particulate and chemical pollutants, biological contamination and building operation can influence indoor environmental conditions and building-related symptoms. Ventilation should therefore be integrated with pollutant-source control, filtration, moisture management, preventive maintenance, appropriate environmental monitoring and organisational accountability. CO₂ remains valuable as an indicator of occupancy-related ventilation performance, but it should not be interpreted as a comprehensive measure of IAQ. Similarly, contemporary attention to PM_{2.5} should complement rather than be conflated with the existing Malaysian respirable-particulate criterion. Strengthening preventive IAQ

management does not require rejection of the existing Malaysian framework; rather, it requires translating its preventive principles into continuous building operation so that foreseeable environmental deficiencies can be identified and controlled before persistent occupant complaints or adverse conditions emerge.

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1. Introduction

Indoor air quality (IAQ) cannot be adequately characterised by a single pollutant measurement, a ventilation indicator or the perceived thermal comfort of an air-conditioned space. Indoor environments are dynamic systems in which building design, occupancy, human activities, furnishing and construction materials, outdoor environmental conditions, ventilation, temperature, humidity, filtration, cleaning practices and mechanical-system performance interact continuously. The environmental conditions experienced by occupants therefore reflect the combined performance of numerous building and operational factors rather than the status of any single parameter. International comparisons of IAQ standards similarly demonstrate substantial variation in the pollutants, measurement conditions and concentration limits adopted by different frameworks, reinforcing the importance of interpreting individual parameters according to their intended purpose and exposure context^[1].

Malaysia has an established occupational framework for IAQ through the Department of Occupational Safety and Health (DOSH) *Industry Code of Practice on Indoor Air Quality 2010* (ICOP IAQ 2010). The Code establishes acceptable ranges or limits for selected physical, chemical and biological parameters and provides a structured mechanism for identifying, evaluating and controlling IAQ problems. It addresses not only environmental measurement but also complaint investigation, walkthrough inspection, pollutant-source identification, microbial contamination, ventilation, renovation, housekeeping, training, record keeping, and inspection and maintenance of mechanical ventilation and air-conditioning systems^[2]. Recent Malaysian studies continue to use ICOP IAQ 2010 as an important reference framework for workplace investigations, including research conducted in offices and healthcare environments^{[3][4][5]}.

The existing Malaysian framework should therefore not be characterised as inherently reactive. Several of its provisions are preventive in nature, including attention to contaminant-source control, water leaks,

microbial contamination, fresh-air ventilation, MVAC maintenance, excessive occupancy and changes associated with renovation^[2]. The more relevant concern is whether these preventive principles are sufficiently embedded in routine building management. Where ventilation, moisture, occupancy and contaminant sources receive substantial attention only after occupant report discomfort, respiratory irritation, unusual odours or visible contamination, complaints may effectively become the event that activates a more comprehensive examination of the indoor environment.

Reliance on complaints as the principal means of discovering environmental deficiencies can delay intervention until adverse conditions have already developed. A preventive approach does not diminish the importance of occupant reports, which remain an important source of environmental and health information; rather, it places complaint investigation within a broader system of routine risk identification, maintenance, monitoring and corrective action. Such an approach is consistent with contemporary Malaysian scholarship that recognises the overlapping contributions of environmental assessment, occupational chemical risk and building operation to workplace health^[6].

This commentary argues that preventive IAQ management in Malaysian buildings should be strengthened through an integrated approach to ventilation, pollutant-source control, particulate and chemical contamination, moisture, filtration, maintenance and environmental surveillance. Particular emphasis is placed on avoiding several common conceptual simplifications: equating air-conditioning with ventilation, interpreting CO₂ as an overall IAQ score, assuming that outdoor air is invariably clean, and treating environmental measurements as substitutes for investigation of underlying building conditions.

2. Ventilation as a Central but Non-Exclusive Determinant of IAQ

Ventilation is among the most directly manageable determinants of indoor environmental conditions because it affects the dilution, distribution and removal of contaminants generated within occupied spaces. Occupants contribute CO₂, moisture, heat and bioeffluents, while furnishings, equipment, construction materials, cleaning products and indoor activities may introduce additional chemical or particulate contaminants. Where contaminant generation is not adequately controlled or balanced by effective removal, indoor concentrations may increase. Contemporary reviews therefore continue to identify ventilation as an important component of healthy indoor environments while emphasising that its effectiveness depends on building design, air distribution, pollutant sources and actual operational conditions^{[7][8]}.

Ventilation requirements are also inseparable from occupancy, as a space originally designed for one occupancy level may subsequently contain additional workstations, experience higher visitor volumes or undergo changes in room configuration that affect air distribution. Consequently, a building cannot be assumed to remain adequately ventilated merely because its ventilation system satisfied design requirements when it was commissioned. ICOP IAQ 2010 recognises this principle by identifying excessive occupancy relative to original design and renovations involving significant ventilation changes as circumstances requiring further IAQ consideration^[2].

Evidence from Malaysian healthcare environments demonstrates the importance of this operational perspective. Ibrahim et al.^[9], in a multistage cross-sectional investigation of six Malaysian public hospital outpatient departments, measured temperature, relative humidity, air velocity, CO₂, total bacterial count and total fungal count and examined their relationships with occupant behaviour. Occupant density was positively correlated with temperature and CO₂, while activities and the operation of windows, doors, fans and air-conditioning were associated with changes in several measured IAQ parameters. The findings reinforce the proposition that indoor environmental performance is shaped not only by installed building systems but also by actual occupancy and the manner in which those systems and building envelopes are operated.

A related Malaysian review by Ibrahim et al.^[10] identified ventilation design, outdoor-air intake, maintenance, building operation and occupant-related factors as interconnected determinants of hospital IAQ. This systems-based interpretation is particularly useful because it avoids treating ventilation as an isolated engineering variable. Changes to occupancy, maintenance, building envelopes and human behaviour may alter effective ventilation conditions even where the underlying mechanical equipment remains unchanged.

The distinction between cooling and ventilation is especially important in Malaysia because mechanically cooled spaces are common and occupants may reasonably associate a comfortable room temperature with satisfactory environmental conditions. Thermal comfort, however, does not demonstrate that an appropriate quantity of outdoor air is entering the room. Split-unit air-conditioning systems primarily cool and recirculate indoor air and therefore should not be assumed, solely by virtue of their operation, to provide adequate controlled outdoor-air ventilation^{[3][5]}.

Recent Malaysian office data illustrate the practical relevance of this distinction. Abd Razak et al.^[5] evaluated IAQ and sick building syndrome (SBS) symptoms among 124 workers in six Malaysian bank

offices and reported higher PM_{2.5} and CO₂ concentrations in offices using split-unit air-conditioning than in offices using air-conditioning and mechanical ventilation systems. The study further reported that building-related symptoms were more prevalent in environments characterised by poorer ventilation and low air movement, while dizziness was associated with several measured pollutants, including PM_{2.5}, PM₁₀, CO₂ and formaldehyde^[5]. These findings should not be generalised to imply that every split-unit system produces poor IAQ or that mechanical ventilation automatically ensures satisfactory conditions; rather, they demonstrate why cooling performance cannot be used as a surrogate for ventilation adequacy or overall IAQ.

Ventilation should therefore be situated within a wider hierarchy of environmental control. Increasing outdoor-air supply may be appropriate where internally generated contaminants require dilution, but ventilation cannot indefinitely compensate for a substantial pollutant source that could reasonably be removed, substituted, isolated or otherwise controlled. The practical objective should be to combine appropriate ventilation with source control, filtration, moisture management and maintenance so that the building system addresses both contaminant generation and contaminant removal.

3. Interpreting CO₂ Within Its Proper Role

The increasing availability of portable environmental monitors has made CO₂ one of the most visible IAQ-related measurements. This development has practical advantages because, in normally occupied spaces where human metabolism is the dominant indoor CO₂ source, temporal changes in CO₂ can provide useful information concerning the relationship between occupancy and outdoor-air ventilation. The limitation arises when this useful operational indicator is interpreted as though it provides a comprehensive assessment of indoor environmental quality^[11].

ICOP IAQ 2010 appropriately places CO₂ under the category of a ventilation performance indicator, rather than treating it as equivalent to the chemical contaminants listed in the Code. The Code specifies a ceiling criterion of 1,000 ppm and states that readings above this value indicate inadequate ventilation^[2]. This regulatory classification is important because it recognises that CO₂ has a specific interpretive role.

Contemporary research provides further support for a contextual interpretation. Persily^[11] examined the widespread use of single indoor CO₂ values as measures of ventilation or IAQ and demonstrated that one concentration cannot represent identical ventilation conditions across spaces with different occupancies and ventilation requirements. Expected indoor CO₂ depends on factors such as the number of occupants,

CO₂ generation rates, outdoor ventilation rates and the duration of occupancy. Accordingly, the author proposed a more space-specific approach rather than assuming that one fixed concentration provides a universal assessment applicable to every building.

Mendell et al.^[12] subsequently reviewed 43 CO₂-based IAQ or ventilation guidelines and identified substantial differences in their purposes, limits and supporting evidence. Although 1,000 ppm was the most frequently encountered concentration, the review demonstrated that different guidelines were developed to address different objectives and that the evidence did not support treating a single CO₂ threshold as a universal indicator of overall IAQ or health protection^[12].

The implications for everyday building management are significant because a lightly occupied office may maintain relatively low CO₂ while containing formaldehyde emitted from recently installed furniture, volatile organic compounds from products or particulate matter originating outdoors. Conversely, a meeting room occupied by substantially more people than usual may experience an increase in CO₂ because human generation temporarily exceeds the capacity of the available outdoor-air ventilation. Neither situation can be fully interpreted without considering the source, occupancy and ventilation context.

Malaysian studies similarly support multi-parameter interpretation; for example, Abu Mansor et al.^[4], investigating an administrative office at a Malaysian public university, assessed ventilation-performance indicators together with physical and chemical parameters and building-related symptoms rather than relying on CO₂ in isolation. Abd Razak et al.^[5] likewise measured CO₂ alongside PM_{2.5}, PM₁₀, formaldehyde, total volatile organic compounds, temperature and relative humidity. These approaches are consistent with the broader principle that CO₂ contributes valuable information about ventilation but cannot demonstrate the absence of unrelated chemical, particulate or biological hazards.

The appropriate role of routine CO₂ monitoring is therefore neither negligible nor all-encompassing. It can support identification of recurrent occupancy-related ventilation deficiencies, provide information about temporal patterns and prompt further investigation where required. Its scientific and managerial value is greatest when the measurement is interpreted within the characteristics of the space rather than presented as an independent certificate that the indoor air is satisfactory.

4. Moving Towards a Multi-Parameter and Source-Based Interpretation of IAQ

The limitations of single-indicator assessment reinforce the importance of evaluating pollutants according to their sources, exposure pathways and relevance to the building concerned. ICOP IAQ 2010 incorporates physical parameters, selected chemical contaminants, biological contaminants and a ventilation-performance indicator, thereby recognising that IAQ is multidimensional^[2]. Internationally, considerable variation exists among IAQ standards and building-certification systems because their objectives, populations, averaging times and pollutant priorities differ. Wei et al.^[1], in a comparison of 26 building standards and certifications, found substantial differences in the pollutants and concentration criteria incorporated into different frameworks and cautioned against direct comparison of values developed under non-equivalent conditions.

This principle is particularly important for chemical pollutants whose sources may have little relationship with occupant-generated CO₂. Formaldehyde and other volatile organic compounds may originate from furnishings, construction and finishing materials, adhesives, cleaning products or renovation activities^[2]. Workplace activities may introduce further chemical hazards, particularly in laboratories and specialised work environments. Abdullah et al.^[6], from a Malaysian perspective, highlighted the different but potentially complementary roles of chemical health risk assessment and IAQ assessment where workplace chemical exposure and indoor environmental conditions overlap. Such evidence supports a source-based approach in which the characteristics of the workplace guide the selection and interpretation of parameters rather than assuming that every building requires identical monitoring priorities.

Particulate matter deserves particular attention because it may originate both indoors and outdoors. ICOP IAQ 2010 establishes an eight-hour time-weighted average acceptable limit of 0.15 mg/m³ for respirable particulates, but it does not establish a separate PM_{2.5} criterion^[2]. Contemporary environmental health literature increasingly differentiates PM_{2.5} and PM₁₀ because particle size influences penetration, deposition and health relevance. The *WHO Global Air Quality Guidelines* published in 2021 provide health-based recommendations for PM_{2.5} and PM₁₀ on the basis of contemporary epidemiological evidence^[13].

These WHO values should not, however, be presented as though they were Malaysian occupational IAQ limits. The two frameworks have different purposes, exposure contexts and averaging periods. Their relevance to the present discussion lies in the evolution of the scientific evidence regarding fine particles rather than in direct regulatory substitution. Maintaining that distinction is important if newer scientific evidence is to complement rather than confuse the application of existing Malaysian requirements.

Recent reviews support greater attention to particle size, sources and control. Li et al.^[14] identified indoor combustion, human activities, resuspension and outdoor penetration as important sources of indoor particulate matter and noted that indoor-to-outdoor relationships are substantially influenced by human activity and ventilation. The authors identified source control, ventilation and filtration-based air cleaning as principal approaches to reducing indoor particle concentrations.

The importance of particle-size differentiation is further illustrated by Bergmans et al.^[15] who described a strategy for sampling and monitoring size-selective particulate-matter fractions in indoor environments. Their work demonstrates the value of distinguishing particulate fractions when characterising indoor particle conditions and supports the broader need to interpret particulate measurements according to particle size and the monitoring objective.

Felgueiras et al.^[17], in a systematic review of ventilation and airborne particulate matter in urban offices, similarly demonstrated that particulate concentrations should be interpreted alongside ventilation conditions and outdoor environmental characteristics. Office buildings cannot therefore be understood as environmentally isolated spaces; external pollution, infiltration, air exchange and filtration contribute to the concentrations experienced indoors.

The need for multi-parameter assessment is also supported by recent Malaysian evidence. Saidin et al.^[3] evaluated multiple IAQ hazards in Malaysian bank offices, while Abd Razak et al.^[5] subsequently incorporated PM_{2.5}, PM₁₀, CO₂, formaldehyde, TVOC, temperature and relative humidity in their analysis of building-related symptoms. Rather than identifying one parameter as universally dominant, these studies demonstrate the importance of examining combinations of environmental conditions relevant to the building and its occupants^{[3][5]}.

5. Outdoor-to-Indoor Pollution and the Need to Integrate Ventilation with Filtration

Outdoor air is indispensable to conventional ventilation strategies, but it should not automatically be equated with uncontaminated air. Ambient concentrations vary according to traffic, industrial emissions, construction, open burning, meteorological conditions and regional pollution episodes. As a result, the effectiveness of outdoor-air ventilation depends partly on the quality of the air entering the building and the degree to which the ventilation system can remove pollutants of concern.

The potential significance of episodic outdoor pollution is illustrated by Gomes et al.^[16], who examined the influence of an extreme Saharan dust event on air quality in western Portugal. Although the study concerned ambient rather than indoor air quality, it provides relevant evidence that particulate conditions in the outdoor environment may change substantially during exceptional pollution events, reinforcing the need to consider temporal variation in outdoor air quality when evaluating air supplied to buildings.

Recent review evidence supports this relationship, with Mohammadi and Calautit^[17] identifying natural ventilation, mechanical ventilation and infiltration as the principal pathways through which pollutants are exchanged between outdoor and indoor environments, while meteorological conditions, building design, ventilation strategy and outdoor sources modify the extent of transmission. Li et al.^[14] likewise identified outdoor penetration and air exchange as important determinants of indoor particulate concentrations and emphasised that source control, appropriate ventilation and filtration-based air cleaning may need to be considered together when outdoor particulate pollution is elevated. These findings support an integrated approach in which ventilation rate, outdoor-air quality and filtration performance are evaluated as related components of IAQ management.

The issue has direct relevance to Malaysia because ambient air quality is spatially and temporally variable. Ibrahim et al.^[18] examined pollutant dispersion in Bukit Rambai, Melaka, and Muar, Johor using ambient monitoring and meteorological data from 2015 to 2018. The analysis demonstrated variation in API and PM₁₀ patterns in relation to meteorological and dispersion conditions and documented periods of unhealthy air quality during the study period^[18].

The study by Ibrahim et al.^[18] concerned ambient air pollution and should not be interpreted as an indoor-exposure study. Its relevance to IAQ is narrower: it demonstrates that the quality of air available to

building ventilation systems varies according to local and regional environmental conditions. This distinction is particularly important when using ambient studies within an IAQ commentary because evidence of outdoor pollution does not establish the magnitude of subsequent indoor exposure.

The respiratory-health relevance of ambient pollution in the same Malaysian regional context has also been examined. Ibrahim^[19] analysed associations between major ambient pollutants and acute respiratory infection outpatient visits in Bukit Rambai, Muar and Bandar Penawar. Relationships differed among locations, while PM₁₀ was the only pollutant showing a significant positive association with ARI outpatient visits across all three study areas^[19]. The results again relate to ambient rather than indoor exposure and therefore cannot be used to attribute the observed outpatient outcomes to indoor PM. They nevertheless reinforce the relevance of particulate pollution to environmental health management in Malaysian settings.

Taken together, the indoor and ambient evidence supports a more nuanced approach to ventilation. Increasing outdoor-air supply may be beneficial for the dilution of pollutants generated indoors when ambient conditions are favourable, whereas periods of elevated outdoor particulate pollution may require greater attention to filtration efficiency, air-intake location and system operation. Preventive IAQ management should therefore avoid treating ventilation rate and outdoor-air quality as independent considerations.

6. Humidity, Moisture and Biological Contamination in a Tropical Building Context

Malaysia's hot and humid climate creates particular difficulties for IAQ management because outdoor air introduced into mechanically cooled buildings carries both sensible heat and moisture. The mechanical system must therefore provide ventilation while simultaneously maintaining acceptable thermal and humidity conditions. Decisions concerning outdoor-air supply can consequently affect cooling loads, dehumidification requirements, energy consumption and the potential for moisture accumulation.

Contemporary building research increasingly treats these objectives as interdependent. Al Mindeel et al. ^[20], reviewing multi-objective optimisation research, described energy consumption, thermal comfort and IAQ as potentially competing but interdependent building-performance objectives. Most studies included in their review attempted to optimise more than one of these objectives simultaneously,

reflecting the practical difficulty of improving environmental conditions while minimising energy consumption.

Niza et al.^[8] reached a related conclusion in a systematic review examining air quality and ventilation in healthy and sustainable urban environments. Their findings emphasised that effective ventilation requires attention to pollutant control, air distribution, humidity, thermal conditions and energy demand and that ventilation strategies should be adapted to the climatic and operational characteristics of the building rather than applied uniformly^[8].

Moisture management is particularly important because fungal growth on building materials is strongly influenced by environmental moisture and humidity, together with temperature, substrate characteristics and exposure time. Lai et al.^[21], in a methodological review of mould-growth experiments on building materials, emphasised the importance of moisture-related conditions in determining mould development and the need for reliable approaches to evaluating mould risk in the built environment. In hot and humid settings, these relationships strengthen the case for early control of water intrusion, condensation and drainage deficiencies rather than relying on remediation only after visible growth has become established.

The relevance of fungal contamination has also been demonstrated in Malaysian healthcare settings. Ahmad et al.^[22] assessed fungi in indoor and outdoor environments at four selected hospitals in Peninsular Malaysia and reported substantial variation in fungal burdens across locations, with two investigated locations exceeding national guideline values. These findings provide contemporary local evidence that biological contamination remains a relevant component of IAQ management, particularly in complex healthcare environments.

Evidence from Malaysian educational environments further demonstrates the complexity of biological and chemical exposures. Zhang et al.^[23], in a multicentre study involving 1,139 students in schools across Johor Bahru, Terengganu and Penang, evaluated indoor pollutants together with microbial taxa and metabolites. Indoor NO₂, CO₂ and indoor dust characteristics were associated with SBS outcomes, while microbial and metabolomic analyses demonstrated that building-related symptoms may occur within a considerably more complex exposure environment than conventional single-pollutant assessment can represent.

Importantly, microbial measurement should not displace investigation of moisture sources. Mendell and Adams^[24] reviewed the use of airborne spore counts for identifying dampness or mould and concluded

that existing evidence did not validate commonly used interpretations of total spore counts for identifying dampness in individual homes. Their findings support the importance of observable building inspection and professional judgement rather than allowing microbiological measurements to become substitutes for investigating leaks, condensation and other moisture-related defects.

The practical priority in Malaysian buildings should therefore be the prevention of persistent moisture through timely control of leaks, condensation, drainage deficiencies and damp materials. Remediation that addresses visible fungal growth without correcting the moisture source may improve appearance while leaving the environmental conditions responsible for recurrence unchanged.

7. Preventive Maintenance as an IAQ Control Measure

Maintenance represents one of the most important mechanisms through which building design is translated into actual environmental performance. A ventilation or air-conditioning system may continue to produce acceptable cooling even when other aspects of its IAQ performance deteriorate. Filters may become heavily loaded, outdoor-air dampers may operate incorrectly, coils may accumulate contamination, condensate drainage may be impaired and changes to internal layouts may alter intended airflow. These conditions may not produce an immediate mechanical failure and therefore may remain undetected where maintenance performance is evaluated primarily through equipment uptime or thermal complaints.

ICOP IAQ 2010 explicitly incorporates inspection and maintenance of mechanical ventilation and air-conditioning systems within IAQ control, demonstrating that maintenance is not peripheral to the Malaysian framework^[2]. Recent Malaysian literature further supports this emphasis, as Ibrahim et al.^[10] identified ventilation-system operation and maintenance among the important modifiable determinants of hospital IAQ, while the subsequent empirical study by Ibrahim et al.^[9] showed how operational behaviour interacts with measured indoor conditions.

Preventive maintenance should consequently evaluate environmental functions rather than concentrating exclusively on whether mechanical equipment remains operational. Filter condition, outdoor-air intakes, dampers, cooling coils, condensate drainage, moisture accumulation and air distribution all have potential implications for IAQ. Changes in room use and occupancy should also prompt reconsideration of whether existing air distribution and ventilation remain appropriate.

This approach requires organisational coordination because the relevant responsibilities frequently cross administrative boundaries. Building and facilities personnel may control equipment and maintenance contracts, occupational safety and health personnel may manage workplace risk, IAQ assessors may undertake specialist investigations, and organisational management may control resources and operational priorities. Effective prevention therefore depends on clearly allocated responsibilities and communication among these functions rather than assuming that satisfactory equipment operation automatically produces satisfactory IAQ.

8. Environmental Monitoring as a Preventive Tool Rather Than a Substitute for Assessment

Advances in low-cost environmental sensing provide building managers with opportunities to identify temporal patterns that may not be apparent during occasional spot measurements. Parameters such as CO₂, PM_{2.5}, temperature and relative humidity can increasingly be monitored continuously or at frequent intervals, allowing recurring changes associated with occupancy, outdoor pollution or mechanical operation to be identified.

The availability of such technologies should nevertheless be accompanied by appropriate expectations concerning data quality. Sá et al.^[25], in a review of low-cost technology for IAQ monitoring, found that such devices may provide useful information for indoor microenvironments but that performance varies and comparison with higher-quality instruments remains important. The authors therefore supported cautious use of low-cost sensing technology rather than treating it as equivalent to reference-grade measurement.

Wang et al.^[26] likewise reviewed real-time sensors for characterising dynamic indoor air pollution and highlighted the advantages of high temporal resolution for understanding changing indoor concentrations. At the same time, the review identified calibration, sensor performance and stability as continuing challenges. These limitations are important where inexpensive consumer devices are used to support workplace decisions because apparent numerical precision should not be mistaken for analytical certainty^[26].

Routine monitoring is most useful when measurements are embedded within a clear decision process. Repeated CO₂ elevations under predictable occupancy conditions may warrant examination of ventilation and room capacity, while persistent relative-humidity abnormalities should prompt investigation of

moisture and mechanical operation. Increases in indoor PM_{2.5} during periods of elevated ambient pollution may warrant evaluation of filtration and outdoor-air intake. Monitoring data acquire preventive value when they lead to investigation and corrective action rather than merely being displayed or archived.

Routine environmental surveillance should also remain conceptually distinct from formal IAQ assessment. A monitor capable of measuring CO₂, PM_{2.5}, temperature and humidity cannot establish the absence of formaldehyde, other volatile organic compounds or biological contamination that it does not measure. Formal IAQ assessment additionally involves consideration of potential sources, building conditions, ventilation and occupant information. Preventive monitoring can therefore assist early identification and prioritisation without replacing a competent investigation when circumstances require one.

9. Health, Building-Related Symptoms and Organisational Performance

The primary justification for IAQ management is protection of occupant health and well-being. Contemporary research, however, also suggests that indoor environmental conditions may influence cognitive and productivity-related outcomes, providing an additional organisational rationale for preventive management.

Cedeño Laurent et al.^[27] conducted a prospective longitudinal investigation among 302 office workers in six countries and examined real-time PM_{2.5} and CO₂ measurements in relation to cognitive testing. Higher PM_{2.5} and conditions reflecting lower ventilation were associated with slower response times and reduced performance across several cognitive metrics. Although the findings should not be interpreted as establishing a universal productivity effect applicable to every building or exposure level, they demonstrate that variations in indoor environmental conditions may have consequences beyond conventional symptom reporting.

Kuramochi et al.^[28], in a meta-analysis of five studies involving 3,679 participants, similarly reported improvement in task-performance speed with increasing ventilation rates and a reduction in error rate of smaller magnitude. The authors nevertheless identified differences among task types, reinforcing the need to avoid simplistic claims that a particular ventilation rate guarantees a fixed improvement in productivity.

More recent synthesis has further emphasised this heterogeneity, with Braga et al.^[29], in a systematic review of models relating indoor environmental quality to productivity, identifying substantial variation according to climatic, cultural, methodological and contextual characteristics. Their meta-analysis showed positive relationships overall but high heterogeneity, indicating that productivity effects should be discussed cautiously and with recognition of contextual factors rather than presented as a predictable financial return from IAQ intervention.

Felgueiras et al.^[30] likewise reviewed contemporary office environments and reported associations between several indoor environmental parameters, building-related symptoms and productivity-related outcomes. Their recommendations emphasised periodic control of relevant environmental indicators, avoidance of identified pollution sources and appropriate ventilation and thermal-management strategies.

Local evidence further demonstrates the relevance of building-related symptoms in Malaysian environments. Abu Mansor et al.^[4] identified SBS symptoms among workers in an administrative office at a Malaysian public university, Abd Razak et al.^[5] documented symptoms among Malaysian bank workers, and Zhang et al.^[23] identified substantial SBS prevalence among Malaysian school students. Differences in study populations and methods mean that their estimates should not be combined or interpreted as a national prevalence figure; collectively, however, they establish that building-related health complaints are relevant across several Malaysian indoor settings.

The organisational case for preventive IAQ management should therefore complement, rather than replace, the health rationale. Evidence concerning performance and productivity may help organisations appreciate the broader consequences of indoor environmental conditions, but measures required to manage foreseeable health risks should not depend upon demonstrating an immediate or quantifiable economic return.

10. Reframing Malaysian IAQ Management Around Continuous Prevention

Complaint procedures remain indispensable because occupants experience the indoor environment continuously and may identify odours, discomfort, symptoms or changing conditions that environmental monitoring does not detect. ICOP IAQ 2010 appropriately provides mechanisms for

receiving and investigating IAQ complaints, and these provisions should remain an important component of workplace environmental management^[2].

The limitation arises when occupant complaints become the principal mechanism through which environmental deficiencies are first identified, because intervention may then occur only after adverse indoor conditions have already become established. A preventive approach requires earlier identification and management of foreseeable risks through routine consideration of ventilation adequacy, occupancy patterns, moisture conditions, pollutant sources and mechanical-system performance. Such an approach shifts IAQ management from episodic investigation towards continuous risk prevention while retaining complaint data as one important component of the overall surveillance system.

In practical terms, changes in occupancy should trigger consideration of whether existing ventilation remains appropriate before recurring CO₂ elevation or discomfort occurs. Renovation should include consideration of material emissions, air distribution and potential pollutant pathways before normal occupancy resumes. Water intrusion and persistent condensation should be addressed before microbial contamination becomes extensive, while MVAC maintenance should consider filtration, outdoor-air supply, drainage and cleanliness rather than focusing solely on cooling performance. Selective environmental monitoring may then provide an additional mechanism for identifying recurring deviations that warrant investigation^[2].

The available Malaysian evidence provides support for such an integrated model. Ibrahim et al.^[10] ^[9] demonstrate that building design, system operation, occupant density and behaviour are interconnected; Abdullah et al.^[6] highlights the potential need to integrate different occupational risk-assessment perspectives; while Saidin et al.^[3], Abu Mansor et al.^[4] and Abd Razak et al.^[5] illustrate the value of multi-parameter assessment in Malaysian workplaces. Recent studies of Malaysian hospitals and schools further demonstrate that microbial and other biological factors remain relevant and may interact with conventional physical and chemical indicators^{[22][23]}.

Effective prevention consequently requires organisational governance capable of integrating engineering, maintenance, occupational health, environmental monitoring and management responsibilities. Where these responsibilities are distributed across separate departments or external contractors, explicit coordination is necessary to ensure that environmental performance is not lost between administrative functions. The objective is not continuous measurement of every possible

contaminant, which would be neither practical nor scientifically justified, but systematic recognition of foreseeable sources and conditions followed by proportionate monitoring, investigation and control.

11. Implications for Future Malaysian Practice

ICOP IAQ 2010 remains an important technical and operational foundation for Malaysian workplace IAQ. Its publication date alone does not invalidate the framework, particularly where it continues to be the principal code used by DOSH and contemporary Malaysian researchers. Nevertheless, scientific knowledge and building-management technology have developed substantially since its introduction.

Current literature places considerably greater emphasis on PM_{2.5}, outdoor-to-indoor particle transport, filtration, dynamic ventilation performance, low-cost environmental sensing and the limitations of universal CO₂ thresholds^{[17][11][7][14][26][12]}. At the same time, research into energy-efficient buildings increasingly recognises that IAQ, thermal comfort and energy consumption must be managed as related objectives rather than independently^{[20][8]}.

The Malaysian evidence base has also expanded, with recent studies examining offices, banks, hospitals, universities and schools and documenting relationships involving ventilation, occupant behaviour, chemical and particulate pollutants, fungal contamination and building-related symptoms^{[10][9][3][4][6][5][22][23]}. This expanding local evidence creates an opportunity to refine future guidance without assuming that international guideline values can simply replace existing Malaysian criteria.

Future Malaysian IAQ practice could therefore provide greater clarity regarding the role and limitations of routine CO₂ monitoring, the supplementary interpretation of PM_{2.5} alongside the existing respirable-particulate framework, filtration strategies during periods of elevated ambient pollution, preventive moisture management, and integration of IAQ with building-energy objectives. Building-specific guidance may also be valuable because offices, hospitals, laboratories, educational institutions and public buildings differ considerably in occupancy, pollutant sources, vulnerable populations and ventilation requirements.

The development of future policy should preserve the distinction between regulatory compliance criteria, health-based international guidance and emerging research metrics. Incorporating contemporary scientific evidence does not require treating every new parameter as an immediate regulatory limit; rather, it requires a transparent understanding of how newer evidence can support risk assessment, surveillance and future revision of established practice.

12. Conclusion

Indoor air quality is produced through interactions among ventilation, occupancy, outdoor air, pollutant sources, particulate matter, chemical contaminants, temperature, humidity, biological contamination, filtration and mechanical-system operation. It therefore cannot be adequately represented by a single environmental measurement or inferred from the thermal comfort of an air-conditioned room.

Ventilation remains one of the most important operational controls because it influences the dilution and removal of contaminants generated within occupied spaces. Its effectiveness, however, depends on actual occupancy, system operation, pollutant sources, outdoor-air quality and filtration. Appropriate ventilation should therefore be understood as one component of a broader control strategy rather than as an independent guarantee of good IAQ.

CO₂ provides useful information concerning occupancy-related ventilation performance, but contemporary evidence supports interpreting it according to building and occupancy context rather than treating one concentration as a universal measure of overall IAQ. Similarly, the increasing health and research emphasis on PM_{2.5} should inform contemporary IAQ practice without incorrectly substituting WHO ambient-air recommendations for the existing Malaysian occupational respirable-particulate criterion.

Malaysia's hot and humid climatic conditions further strengthen the need for integrated management because outdoor-air ventilation interacts with cooling, dehumidification, moisture control and energy consumption. Persistent moisture and inadequate maintenance may contribute to microbial and other IAQ problems even when mechanical equipment continues to provide satisfactory cooling. Preventive maintenance, filtration and moisture control should therefore be considered components of occupational and environmental health protection rather than solely engineering functions.

Although ICOP IAQ 2010 already provides important preventive foundations, the principal opportunity for improvement lies in ensuring that these principles are translated into continuous building practice through systematic attention to occupancy, ventilation, pollutant sources, moisture, maintenance, environmental monitoring and organisational responsibility. Occupant complaints should remain an essential surveillance mechanism, but they should operate alongside rather than substitute for preventive management.

A mature IAQ system should therefore be evaluated not only according to how effectively an organisation responds when a complaint is received, but also according to whether foreseeable environmental

deficiencies are identified and controlled before they become persistent. In the Malaysian context, strengthening this preventive orientation offers a defensible pathway for integrating the existing regulatory framework with contemporary scientific evidence while maintaining clear distinctions between established compliance requirements and emerging environmental health knowledge.

Statements and Declarations

Funding

This work received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Potential Competing Interests

The author declares no competing financial or non-financial interests.

Ethics

Not applicable. This commentary does not report primary research involving human participants or animals.

Data Availability

No new datasets were generated or analysed for this commentary.

Author Contributions

The author conceptualised the commentary, conducted the literature synthesis, drafted the manuscript and critically revised the content.

Disclaimer

The views expressed in this commentary are those of the author and do not necessarily represent the official position of the Ministry of Health Malaysia or any affiliated institution.

Acknowledgements

The author acknowledges the professional experiences and scholarly engagement that contributed to the development of the perspectives presented in this commentary.

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Declarations

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.