



Review

Fusing wellness and innovation within eco-friendly structures: An exhaustive critique on tracking and enhancing interior air conditions

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Abstract: This paper illustrates how eco-friendly structures combined with resource-efficient approaches elevate interior air quality (IAQ), the broader interior environmental quality (IEQ), and overall human vitality. The increasing focus on eco-responsible lifestyles has spurred the development of environmentally sound construction practices, which are recognized to conserve power and lower expenses over time. An organized evaluation of 128 refereed articles was undertaken, encompassing investigations into structural planning, component choices, air surveillance innovations, and wellness consequences. Affordable detection units like the Dylos, Foobot, and AirVisual Pro models, alongside linkage protocols including WiFi, LoRa, Bluetooth, and visible light communication (VLC), were evaluated for their operational effectiveness, shortcomings, and applicability in ongoing IAQ supervision. Primary hurdles involve gradual sensor inaccuracies, routine servicing needs, reactions to the surrounding variables, and location-specific compliance restrictions. Sophisticated adjustment frameworks and merging techniques are delved into for improving the precision of information and the equipment's sustainability. The analysis underscores the necessity for an integrated, vitality-centered methodology in eco-construction.

Keywords: power preservation; economical detectors; IAQ sensors; natural layout features; sturdy architectures

1. Introduction

The pursuit of sustainable progress now requires novel strategies that curb ecological harm while elevating personal welfare. Eco-construction methods stand out as a vital countermeasure, weaving

together power savings, ecological mindfulness, and resident-oriented planning across every phase of a facility's existence, from initial sketching and blueprinting through to construction, daily functioning, and eventual dismantling [1–5]. Interior air conditions (IAQ) form a layered concern affected by layout preferences, air distribution mechanisms, material-related decisions, residents' actions, and outside elements. The World Health Organization (WHO) continually advocates for secure, health-preserving habitats accessible to every demographic group. Nevertheless, even with these international guidelines, substantive knowledge voids linger concerning the influence of eco-strategies on IAQ amid assorted facility categories and atmospheric settings [6]. Layout options, including facility alignment, air passage routes, and interconnecting zones, immediately shape wind currents and the scattering of contaminants. Concurrently, selecting minimal-release materials and coatings markedly diminishes the accumulation of interior toxins [7,8]. Moreover, the expanding presence of detector-driven IAQ management systems—apparatuses that gauge and track metrics like particulate matter (PM)_{2.5}, CO₂, volatile organic compounds (VOCs), and warmth/moisture levels—presents fresh avenues for instantaneous environmental regulations. Intelligent systems leveraging WiFi, LoRa, Bluetooth, and visible light communication (VLC) permit nonstop assessment of these contaminants [9–11]. However, variations abound in their capabilities, pricing, energy demands, information trustworthiness, and accessibility for users. Embedding them within facility blueprints frequently encounters obstacles related to uniformity, long-term tuning, and area-based legal conformity [12,13]. Numerous investigations affirm that superior IAQ yields tangible advantages for vitality and output. Accredited eco-facilities reveal diminished occurrences of sick building syndrome (SBS)—a label for assorted ailments connected to time indoors—and gains in mental acuity, rest patterns, and respiratory wellness [14,15]. Still, a portion of research concentrates solely on ecological metrics or vitality results, lacking a cohesive viewpoint. Overcoming this demands us to scrutinize IAQ innovations and structural approaches regarding their engineering attributes alongside their effects on human prosperity. Expanding on this, future designs must anticipate evolving climate patterns, incorporating adaptive features that respond dynamically to external shifts, thereby ensuring long-term efficacy in diverse global regions.

2. Methods

The investigative structure adopts an organized approach for collecting and scrutinizing information via existing materials. In this setting, IAQ within eco-construction for enhanced vitality and satisfaction takes center stage. This effort carefully appraises academic outputs on vitality and innovation in eco-structures for IAQ by a detailed inspection of published works. The primary goal involves compiling and dissecting the existing scholarly collection on eco-facilities, spotlighting areas like IAQ, astute planning, inventive tools, and following steps for superior vitality and satisfaction. Structured literature review protocols were applied that have proven their strength and reliability in previous academic works [16,17]. The review and dialogue process started by defining a precise investigative focus before launching broad material queries. Following that, we executed a thorough search and secured relevant scholarly articles from established repositories such as Web of Science, Scopus, Wiley, IEEE, MDPI, Google Scholar, Springer, and Elsevier ScienceDirect. Search term compilations and full-content evaluations were created for domains covering “eco-construction and vitality”, “IAQ and human effects”, “facility layout and IAQ”, “apparatuses to oversee and advance IAQ”, and “approaches for superior IAQ” (Figure 1). Keyword uses initially produced abundant

scholarly materials. The effort performed an in-depth evaluation of 221 documents, chosen after meticulous screening from selected sources for pertinence to the study's focus. After a close review of the headings, summaries, and entire texts, 93 unrelated entries were removed for failing to match the aims and boundaries of the initial query. The effort deeply analyzed 128 refereed works, encompassing 32 on tangible aspects like planning and assembly, materials, power reduction, natural layouts, and similar. Additionally, 47 works assessed tools to oversee and boost IAQ, while 49 examined vitality concerns tied to IAQ. This offers an all-encompassing breakdown of scholarly outputs, systematically reviewing their focal points, procedures, and conceptual bases. It also conducts a thorough evaluation of connected domains to pinpoint prospective future academic paths. The effort examined influences on IAQ over multiple fields to uncover upcoming investigative prospects and key challenges. Figure 1 depicts the selection and evaluation pathway for the included documents.

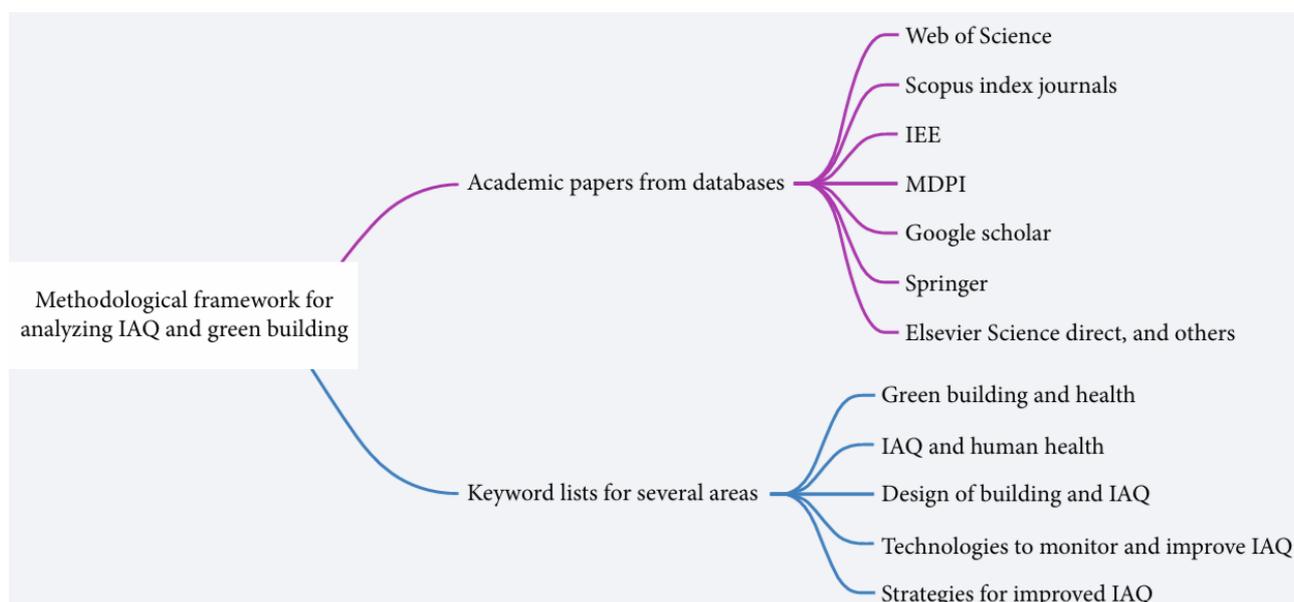


Figure 1. Illustration of the methodological framework employed in this review.

3. Literature review

The essential function of eco-structures in boosting interior environmental quality (IEQ) standards and individual vitality remains unquestionable [18–21]. Besides the social and behavioral elements, ecological concerns, structural planning, management, servicing, and additional aspects may affect residents' wellness [19,22–24]. Moreover, assorted tangible and intangible factors shaping IEQ encompass IAQ, heat regulation, illumination, sound management, and air flow (Figure 2). This illustrates the substantial input from eco-structures featuring an excellent indoor environment that could support improvements in vitality [22,26,27].

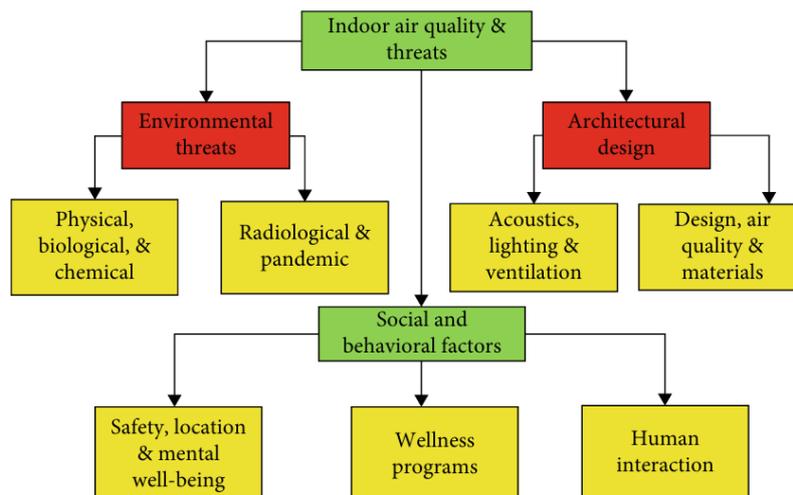


Figure 2. Indoor air quality and threats imposed by the environment, social behaviors, and architectural design [25].

Lately, eco-building has surged in appeal as an approach to trim power usage effectively while improving interior environmental standards and individual vitality. To maintain indoor warmth at optimal points, most trade facilities, towering edifices, and belowground systems rely on automated air circulation mechanisms. Natural mechanisms hold a key position in these by substantially cutting emissions with minimal power draw. Mukhtar et al. [28] investigated air flow planning in subsurface facilities linked to subpar IAQ from restricted circulation. Their work stressed embedding natural planning strategies, including central voids, breeze-guided apertures, and heat-induced uplift systems, during the initial structural phases. These strategies proved to lessen automated air dependence while enhancing circulation and toxin dispersal. The work applied computational fluid dynamics simulations to replicate wind currents and contaminants' movement, providing actionable planning tips for IAQ enhancement in confined areas. Their results reinforce the wider claim that structural planning directly shapes IAQ, particularly in intricate systems like subsurface or crowded edifices [28]. Additional studies likewise indicated that facility-linked components potentially influencing the occupants' wellness cover ecological risks, social and behavioral matters, and management and servicing [29,30]. Assembly techniques and materials that boost residents' ease while slashing the power draw are known to bolster power efficiency within eco-structures (Table 1) [29,31,32].

Table 1. Physical parameters of green building for improved IAQ and wellbeing.

Key performance indicators of green buildings and architecture	References
Design considerations of the building and the built environment for improved health	[8,31,33–40]
Improved ventilation system	[31,36,37,40–43]
Energy efficiency, consumption savings, and improved IAQ	[31,32,36,41,43,44]
Building and construction materials	[32,35,39,42]
Passive design and strategies	[31,32,41,45]
Thermal comfort and lighting strategies	[33,40,41,46]
Importance of life cycle analysis in green buildings	[35,42,45]
Certification of building for better IAQ	[5,35,39,46,47]

Research shows that these steps may cut power usage by 50% alongside improving heat regulation and reducing the risk of airborne threats. These steps further aid sound enhancement, yielding superior focus and psychological outcomes for the occupants [19,31,48].

3.1. Consequences of IAQ

IAQ denotes the indoor air conditions and their effects on individuals' vitality, ease, and output. This creates varied influences across ecology, community, finances, strategic applications of technology, etc. (Figure 2) [49,50].

3.1.1. Ecological

Power-saving steps hold a vital position in curbing ecological effects. These may be supported via instruments for complete heat exchange computations, power simulations, and applying superior facility enclosures [51]. Merging solar-integrated facades, effective lamps, and eco-friendly materials plays a central role in reaching this goal [50,52].

3.1.2. Financial

Power efficiency likewise plays a major role in lowering the financial effects. Substantial savings may be realized through life cycle evaluation techniques, benefit–cost breakdowns, and eco-markups. Additionally, using multi-source systems in facilities, like solar heaters and photovoltaic power production, helps reduce overall life cycle expenses, thus improving the financial viability of sustainable structures [45].

3.1.3. Social

To counter the social effects, creating novel local systems blending traditional aspects into sustainability's social side is crucial [53]. Assessing IEQ via standard benchmarks and using sophisticated techniques like choice comparison trials are key assessment phases. Frameworks combining renewables, optimized power use, light refinement, handling construction waste, water quality management, roof heat mitigation, and exterior plus interior air quality prove useful for reducing the social effects [44].

3.1.4. Power efficiency

Power efficiency and its management have drawn extensive attention in global scholarly and industry investigations. Works from 2011 onward cover broad fields, from output metrics, handling, and savings to renewable source uses in sustainable facilities [54,55]. Although administrations, research bodies, and academic centers have launched many investigations here, no structured overview has unified this information for power-effective sustainable structures [56].

3.1.5. Application of innovations

Innovation proves crucial for power efficiency and uplifting facilities' IEQ. Natural and active planning innovations have been used for cutting power needs and boosting indoor comfort (Table 1). For instance, dual-layer facades have undergone thorough reviews for improving heat output and lessening the demand for heating, ventilation, and air conditioning (HVAC), thus aiding the facilities' sustainability [56]. The latest progress in IAQ management innovations has allowed adaptable and expandable answers in varied contexts. IBM's intelligent facility program merges IAQ detectors with wireless protocols like WiFi and LoRa to track metrics including CO₂, PM_{2.5}, and moisture. The setup permits instant HVAC tweaks, cutting power draw up to 30% while ensuring residents' comfort [57]. Likewise, in home contexts, Bluetooth-capable units like Foobot are integrated into intelligent residence systems to spot high VOC and particle levels. These units dispatch instant notifications via phone apps, encouraging behavioral shifts like boosting air flow or using low-release cleaners [58]. On the city level, Paris' intelligent urban effort applied LoRaWAN-capable IAQ detectors to evaluate the area's air conditions across 12 months. The setup achieved a 90% match with pro-level stations, showing the technologies' precision and dependability with much lower running expenses. This underscores IAQ management innovations' expandability and flexibility to various city contexts and requirements [9].

3.1.6. Methods and approaches

Various methods have been implemented to boost power efficiency. An all-encompassing overview of comfort and power in intelligent power facilities covers aspects like residents' behavior, tool simulations, regulation systems, and source considerations. Upgrade strategies, featuring natural approaches with evaluation methods (life cycle evaluations plus social and cost evaluations), have undergone critical reviews to identify the best upgrade solutions [40,41].

3.2. *Tangible elements and vitality concerns*

SBS includes assorted ailments like eye irritations, headaches, throat soreness, nose and chest blockage, dizziness, dry skin, and focusing difficulties commonly tied to extended contact with subpar indoor environments. Though these ailments may not always hinder routine tasks, they frequently cause lowered output, discontent, and more vitality-linked grievances at work [11,14,59]. In graver situations, subpar IAQ is linked to sudden and ongoing vitality outcomes, covering asthma, weariness, allergies, nausea, and even cancer threats, depending on the type of toxin and length of exposure. Tangible metrics like warmth, moisture, air flow rate, and wind speed prove essential to IAQ and individual vitality. For example, excess indoor warmth is tied to mental weariness and weakened task execution [60–62], whereas low moisture may irritate membranes and high moisture can foster mold, adding to respiratory problems [62–65]. Weak air flow heightens indoor toxin buildup, thus increasing SBS-linked ailments like headaches, eye discomfort, and weariness [4]. These results hold special relevance in confined spots like education centers, care units, and work areas, where people frequently face enclosed air over long durations.

3.2.1. Structural planning and IAQ

Indoor security involves reducing the tangible, chemical, biological, and mental risks that may harm individuals' vitality and enjoyment. These risks cover contact with air toxins like PM_{2.5} and VOCs, heat stress, microbial growth, poor illumination, and accident risks [15,66]. Moreover, indoor security includes mental sides like sensed comfort, control, and safety, all influencing psyche, output, and quality of life [66–68]. Securing a safe indoor environment demands a multi-angle method merging facility output markers like IAQ, heat regulation, sound management, and light standards, particularly in vulnerable spots like education, care, and work venues [69,70]. The building site also holds a key position in indoor security, with factors covering nearness to toxins' origins, green area access, and clean exterior air availability. Additionally, vitality initiatives advancing IAQ knowledge, healthy resident actions, and planned servicing schedules can greatly improve overall security and environmental standards. These efforts aid IAQ's tangible sides and psychological satisfaction by creating comfortable, stress-lowering indoor areas supporting mental operations, social exchanges, and teamwork settings [15,60]. Together, such merged steps boost residents' contentment, lower health-related grievances, and raise output, ultimately stressing the need to prioritize security and satisfaction in interior environment planning. Structural planning remains crucial for practical, visually appealing, and vitality-supporting indoor environments. The main factors cover sound management, air flow, illumination, choice of materials, layout, activity encouragement, and IAQ (Table 1). Sound planning manages noise for clear exchanges, while proper illumination boosts comfortable vision. Air flow guarantees fresh air and toxin clearance. Low-release materials are selected for sustainability and IAQ. Layout emphasizes utility and satisfaction, encouraging activity. IAQ is upheld by air flow, fresh air, toxin clearance, sustainability, etc. (Figure 3).

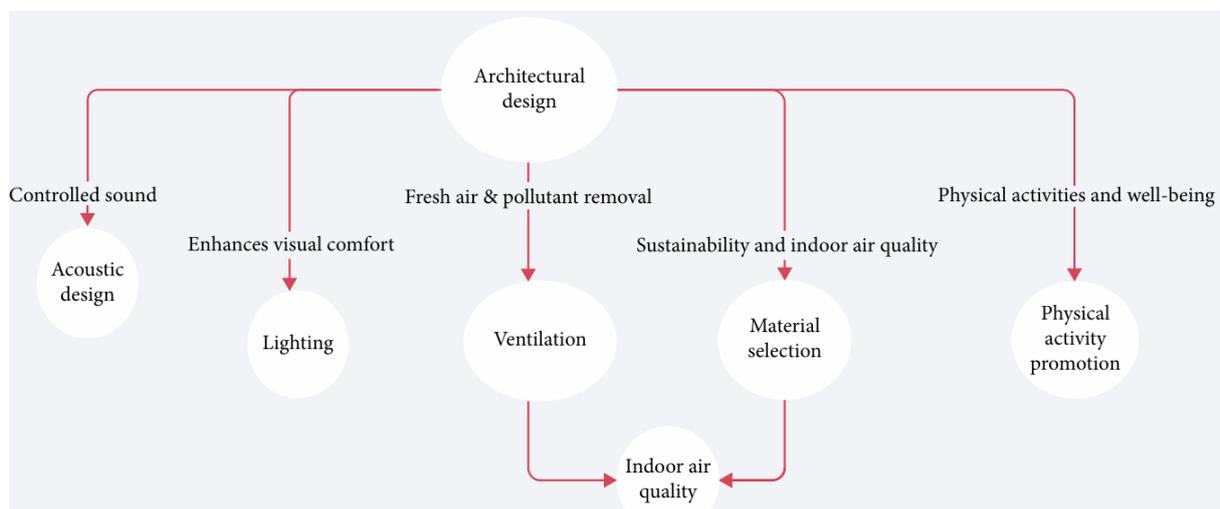


Figure 3. Illustration of architectural design to improve indoor air quality.

Merging these elements yields healthier and more sustainable areas [11,29,48,71,72]. Chatzidiakou et al. stressed residents' behavior and structural planning's role in power efficiency within national power use goals [36]. They probed power efficiency, toxin amounts, and air efficacy, considering SBS and respiratory symptoms in the rooms of two Greater London education centers.

They gauged PM, warmth, VOCs, O₂, NO₂, and O₃ during warm periods. Respiratory issues appeared common in centers, and they identified positive links between contact with NO₂ and PM and the dominant health outcomes. The odds ratio (OR) of asthma stood at 1.4 with a confidence interval (CI). Conversely, rates of skin issues showed an OR and CI of 1.3 and 95%, respectively. Elevated heat and higher contact with CO₂ and NO₂ may also cause mold allergies and respiratory symptoms [36,73]. Thus, they advised merging temperature regulation and IAQ for better outcomes [36]. Increasing air flow rates could cut SBS symptoms. This achieves via reducing indoor CO₂ and handling excess heat. Planners and builders may enhance the layout, servicing, and upgrades of education facilities. People near busy roads face a higher risk of contact with NO₂. Hence, this should be factored into planning or existing remodels of educational facilities. Improving IAQ in cultural venues and facilities proves challenging, rendering power efficiency a chief issue. IAQ exceeds the norms in such facilities in terms of warmth, CO₂ levels, and moisture levels. It indicates that merely using eco or renewable power fails to render a facility energy-efficient [74].

4. Discussion

4.1. Strategies for power refinement in eco-facilities

Natural approaches like sunshades, building alignment, and isolation improve temperature comfort and lessen reliance on HVAC [75]. Active approaches cover need-based air flow and intelligent building management systems (IBMSs) that adjust HVAC via instant IAQ information [76,77]. For example, a Singapore facility cut its yearly power draw by 32% by merging sun-adaptive facades with flexible air systems [78,79]. Additionally, adjustable facades, especially smart air and exterior shading, may trim power draw by 19.87%, 22.37%, 15.19%, and 9.23% across four atmospheric zones of China [80]. Asere and Blumberga [43] ran a system dynamics simulation for power-cutting steps in public facilities and evaluated efficiency and IAQ issues. The simulation layout revealed how loops, nonlinearity, and lags alter behavior. They noted it influences IAQ, and public building efficiency strategies usually reduce national power draw and emissions. Conversely, it diminishes IAQ and facility output. Here, automated air boosts indoor air standards and output, though it is costly. The simulation further indicated the function of national air norms, with public buildings' power use up 1.3% in 2014 and 2.1% by 2040. Compared with no automated air, CO₂ outputs reach 7050 t/year [43]. When efficiency steps accelerate, the gap between options widens. Licina and Langer also noted that eco-facility accreditation programs advance IAQ [46]. Adopting the wellness-focused program sparked research on IAQ effects. They combined on-site tracking and resident feedback to appraise accredited work facilities. The work followed full-time staff moving from unaccredited to accredited systems. Tangible gauges showed that all facilities featured activity encouragement strategies to increase IAQ, like superior filters, yet outer air standards frequently demand strict measures for maximum IAQ [81], such as minimal PM, SO₂, NO₂, and CO₂ irrespective of accreditation. All air toxins complied with global norms. However, eco-badges showed no impact, with accredited facilities being higher in total VOCs, and many organics were over the limits. They advised requiring low-release materials to reduce contact with VOCs [46]. With IAQ, accredited facilities showed greater resident comfort than standard and unaccredited ones. Temperature comfort, alongside other environmental elements, likely aided this finding [46]. Furthermore, multiple works clarify that eco-facilities planned with best air flow, safe materials, and merged IAQ management systems typically

show better IAQ than standard ones. Key comparison metrics frequently involve the amount of VOCs, CO₂, and particles plus other indoor toxins [14,63]. Superior IAQ in eco-facilities is linked to improved resident vitality, fewer SBS ailments, and boosted output and comfort. Conversely, standard facilities, particularly aged ones, might lack advanced air and filter systems optimizing IAQ, possibly causing lower resident comfort. Here, studies have shown that US eco-facilities, accredited via Leadership in Energy and Environmental Design (LEED)-like norms, are tied to superior IAQ resulting from strict air and material-related rules, yielding lower indoor toxins [47]. Meanwhile, China faces outdoor air challenges affecting IAQ. Eco-facilities use smart modeling, especially for increasing IAQ and IEQ in eco-facilities, which has proven very practical in advanced countries thanks to technological progress, building standards, skills, and funds [82,83]. These countries usually hold cutting-edge technology and systems enabling smart modeling and information analysis for eco-facilities. Advanced nations frequently enforce tough rules and directives requiring specific ecological protection and health standards, which smart modeling handles well. Plus, the availability of funds and skills lets them create intelligent and sustainable building solutions. For example, Siemens crafted building technology using smart modeling to oversee and refine operations. The Desigo CC system oversees and tracks varied building systems to refine output and power use, aiding sustainability and better IAQ [84]. Though it involves large upfront costs, the extended savings in power and running expenses, plus gains in resident satisfaction, support smart modeling in eco-facilities. Briefly, eco-building stresses vitality and features the adoption of amenities and smart modeling to increase occupant satisfaction. Here, accreditation serves as a fresh ranking method advancing health-focused building planning and management. However, recognizing the contribution of IEQ standards as key remains vital [85,86].

4.2. Innovations for IAQ advancement

Heating, air flow, and cooling systems, or HVAC, are commonly applied for indoor climate management, but frequently limit IAQ management. Though some HVAC systems include purification, their efficacy against pathogens like viruses remains restricted. Innovations hold a central position in tackling these problems (Figure 4).

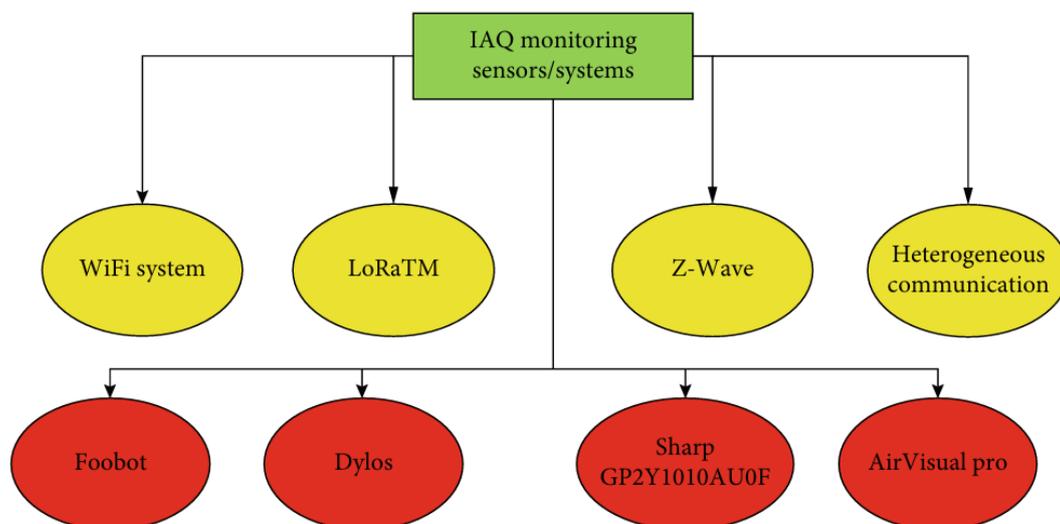


Figure 4. Illustration of technological implementations to improve indoor air quality [25].

Dylos, Foobot, and AirVisual Pro stand as dependable, economical units for tracking PM. Among the assessed low-cost units, Dylos, Foobot, and AirVisual Pro reliably showed strong PM tracking results. These showed medium to high matches with commercial instruments, signaling their dependability for capturing indoor PM. However, Dylos displayed nonlinear reactions and lower sensitivity at elevated PM levels (Figure 4) [58,87]. Sharp GP2Y1010AU0F, a certain PM detector part, often appeared in assessments of PM monitors (Figure 4). This part matched well with comparable tools. It frequently aligned with market low-cost units like Foobot, AirAssure, UBAS, and HAPEX [87,88]. Conversely, low-cost detectors like Sharp GP2Y1010AU0F and others like it carry drawbacks, with tuning being essential for extended precision [89]. Regular tuning preserves accuracy and trustworthiness. Kelly et al. noted cheaper detectors have lower sensitivity than premium ones, possibly missing low PM concentrations [58]. Plus, environmental conditions like moisture and warmth affect many detectors, including cheaper ones [90]. These detectors' working life might shorten, degrading quicker than costly ones [91]. Disruptions challenge detectors, which are vulnerable to other atmospheric components, causing skewed info [92]. WiFi, wireless networking as per IEEE 802.11 norms, ranks top among IAQ management systems [55] (Figure 4). It runs in unlicensed Industrial Scientific and Medical (ISM) (5–60 GHz) bands. Fast, safe links make it ideal for IAQ. It features low costs and compatibility with devices like phones and computers. Dependable, safe, quick, and cheap benefits popularize it for IAQ systems' gateway-to-IoT-server links. Scholars have applied fixes for the disadvantages of WiFi like short range, high cost, and power draw. They use economical, low-power, compact electronics like ESP8266 and ESP32 components. The use of WiFi in IAQ management is optimized via link timing and onboard tools like Raspberry Pi [93]. IAQ management systems often apply low-power, cheap Bluetooth wireless as per IEEE 802.15.1 standards (Figure 4). These enables information transfer between phones and sensor networks plus short links between gateways and detectors via 2.4 GHz unlicensed ISM [94,95]. Around 10% of IAQ setups use bidirectional WiFi, which lets phones access detector data for handling and analyzing values. Bluetooth's cheapness and low power are among the benefits. Weak eavesdrop security, short coverage, interference from other wireless systems are some disadvantages of WiFi. Still, Bluetooth is a useful technological innovation [94–96]. IAQ units can apply LoRa™ wireless systems (Figure 4). These use 868 and 900 MHz ISM at rates of 0.3 to 50 Kb/s. LoRa is suited to outdoor use because of its low cost, low power, and extended battery life. It widely transmits detector data from the IAQ core to the cloud. The adoption of LoRa is complicated versus others, needing mobile gateways [93,96,97]. Moreover, the environmental tracking data risks theft from weak protocols like poor keys and basic authorization, thus it is unsuitable for large smart home uses. Roughly 1 in 10 IAQ systems uses mobile protocols like 2G, 3G, 4G, and General Packet Radio Service (GPRS). Useful mobile management allows interaction with cellular devices. Variable sites need broad coverage, which is difficult with current wireless systems. Sending, receiving, and processing data over vast cellular areas is tied to mobile. Long Term Evolution (LTE) skips intermediaries like gateways/loggers, directing raw data to the servers. Yet mobile systems' high cost and power limit their use for IAQ [93,98,99]. Visible Light Communication (VLC) alternatives include Radio Frequency (RF) wireless for IAQ management, mainly indoors. These use light-emitting diodes (LEDs) for light and wireless technology, which allows interaction within a 6-m light radius indoors, lower electromagnetic disruption, and better data safety via non-RF VLC systems. VLC's applicability is limited to sight-line, direct view areas only. Thus, VLC often alternates with RF for certain areas (Figure 4) [97,100]. Z-wave wireless standards for home/small business automation (Figure 4) are affordable with low energy requirements. However,

it transmits at 40 kbps within a 30-m range only. Z-wave systems get data from detector nodes to central gateways in IAQ systems. Having more Z-wave components per node extend the distance. But the use of Z-wave for IAQ is limited and this frequency is unauthorized in some nations [93,101]. Mixed communication using varied wireless common in IAQ management (Figure 4). Many projects tackle merging forms, thus boosting efficiency better than single systems. IAQ management often uses multiple protocols for interference-free and better data exchange. Data from units to the cloud via a mix of GSM/WiFi allows instant customization per case. Bluetooth supplements mid-/long-distance communication. Low cost and low power make Bluetooth a promising mix with other electronics. Detectors/gateways interact via wireless systems like Bluetooth [97,102]. Mixed communication for tracking IAQ offers benefits, but we must recognize the disadvantages of such systems. Merging many modalities raises the complexity, creating management/troubleshooting challenges [103]. Though parts like Bluetooth incur a modest cost, different protocols add integration/maintenance expenses [104]. Plus, interoperability requires the seamless interaction of different devices/protocols. Compatibility problems limit integrable tool types [105]. Many protocols increase the security risks, needing strong safeguards [106]. Though some systems, like Bluetooth, require less power, sophisticated mixes increase the overall draw [107]. Different methods may cause transmission delays/discrepancies, affecting real-time IAQ monitoring [108]. Some studies used other technologies or detectors for tracking IAQ, including market low-cost commercial component modules and custom units. Low-cost detectors' output varied according to the detectors/tools, conditions, and comparisons. Experimental results showed good cost–benefit ratios. Field conditions are more variable, likely with uncontrolled surroundings and diverse toxins [93,96]. Table 2 details a comparison of the technologies in terms of cost, duration, power, and expandability.

Table 2. Comparison of performance cost, lifespan, power requirements, and scalability of different technologies for monitoring IAQ.

Technology/sensor	Cost	Lifespan	Power requirements	Scalability/use case
Dylos DC1700	Moderate	3–5 years	Low (battery-operated)	Personal/home use; limited by a lack of multipollutant detection [3,58]
Foobot	Moderate	3–5 years	Low (USB-powered)	Smart home integration; real-time alerts [9,58,88]
AirVisual Pro	High	4–6 years	Moderate (wall or USB)	School and commercial use; cloud enabled [58,109]
WiFi (IEEE 802.11)	Low	3–5 years	High (continuous power)	Short range; suitable for dense indoor environments [9,88,109,110]
LoRa	Low moderate	5–10 years	Very low (battery-optimized)	Long-range outdoor monitoring; limited bandwidth [9,111]
Bluetooth	Very low	3–4 years	Very low	Good for mobile apps and wearables; limited data capacity [9,15]
Visible light communication	High	3–4 years	Moderate	Specialized indoor uses; emerging tech, line-of-sight-dependent [9,110]

4.2.1. Pros and cons of low-cost detectors and instruments

The works assessed here stress routine tuning/validation of low-cost detectors/instruments via commercial tools for precise gauges, tuning site-specific factors such as warmth/relative moisture [101,112]. It is vital to tackle the limits and possible drift over time or different states. Despite output differences and the need for calibration with commercial systems, the use of low-cost systems for monitoring IAQ is verified; studies generally endorse low-cost IAQ sensing. Cheapness, reduced power, and ease of use are among the advantages of low-cost detectors/tools. However, they cannot fully stand alone, and need commercial validation and tuning. Technological innovations include the creation of low-cost detectors and smart continuous tuning models [112,113]. Still, many of the assessed low-cost technologies suit qualitative analyses, giving useful insights into IAQ, aiding personal risk management. They also provide tools for alerting users to high toxins, enabling simple fixes and, depending on the sensors' ranges, quantitative tuning via models [101,112,113]. Briefly, the assessed works show low-cost detectors' and instruments' potential for monitoring IAQ. Though the output varies, they provide valuable IAQ insights when tuned and validated properly. Future works should probe their applicability in different indoor spaces, broaden the range of toxins, and increase their precision and reliability.

4.2.2. The role of detectors' life in studies

A detector's working duration is key influence on practicality and economy, especially at a large scale. Low-cost systems may initially be affordable; however, we must consider higher extended costs of their short durability and replacement frequency. Longevity factors include the detector cycle, comparison breakdowns, servicing, reliability/output effects, and financial impacts (Figure 5) [21,114,115].

4.3. Key findings

This systematic review of 128 peer-reviewed studies confirms that green building design strategies and continuous IAQ monitoring significantly enhance IEQ and occupants' wellbeing. The major findings are as follows:

- Passive design features (cross-ventilation, atrium stacks, strategic window placement) combined with low-emission materials reduce indoor PM_{2.5}, VOCs, and CO₂ concentrations by 25–65% compared with conventional buildings.
- Accredited green buildings (LEED, WELL, IGBC, GRIHA) consistently demonstrate fewer SBS symptoms and higher cognitive performance and occupant satisfaction.
- Low-cost sensors (optical PM, NDIR CO₂, MOX TVOC) achieve acceptable accuracy ($R^2 = 0.81–0.96$) after proper field calibration and can enable demand-controlled ventilation savings of 15–35%.
- Communication protocols such as LoRaWAN and hybrid WiFi/Bluetooth networks are the most practical for large-scale, real-time IAQ monitoring in green buildings.

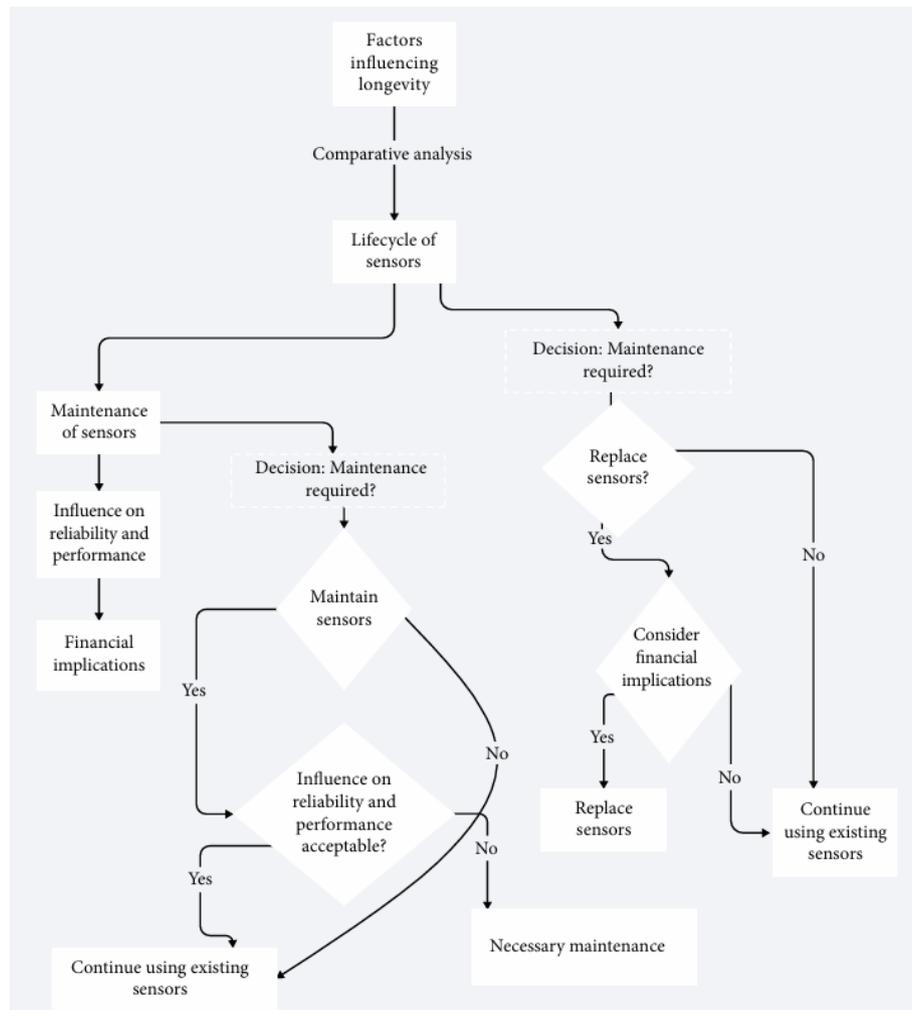


Figure 5. Sensor longevity and factors influencing durability, maintenance, and financial implications [25].

4.4. Practical implications and recommendations

- Architects and consultants in Tier-II and Tier-III Indian cities should prioritize the integration of passive design with sensor-ready infrastructure from the schematic design stage to maximize natural ventilation while retaining the ability to trigger mechanical filtration during high outdoor pollution episodes.
- Building owners and facility managers should deploy hybrid low-cost and reference-grade sensor networks with mandatory quarterly field calibration and cloud-based dashboards that are visible to occupants to simultaneously achieve energy savings and transparency.
- Policymakers and green rating bodies (IGBC, GRIHA) are recommended to make continuous monitoring of at least PM_{2.5} and CO₂ mandatory for all new and existing commercial and educational buildings above 5000 m² by 2030, in line with EU EPBD and Singapore BCA Green Mark 2021 requirements.
- Developers can expect 4–8% higher rental premiums and 2–5-year payback periods for IAQ monitoring systems when combined with demand-controlled HVAC.

4.5. Limitations

This review has several limitations that should be acknowledged:

1. **Reliance on secondary data:** The analysis is based entirely on published studies; no new primary field measurements were conducted.
2. **Geographic bias:** Approximately 68% of the reviewed studies were conducted in Europe, North America, and China; only 11 studies originated from India, limiting direct applicability to local climatic and pollution contexts (e.g., high outdoor PM_{2.5} in northern India).
3. **Variability in low-cost sensors' performance:** Most validation studies were short-term (<6 months) laboratory or controlled field tests; their long-term drift and performance under the extreme humidity/temperature typical of Indian summers remain under-reported.
4. **Lack of standardized calibration protocols:** No universal field calibration method exists for low-cost sensors, making cross-study comparisons difficult.
5. **Limited focus on occupant behavior:** Few studies have quantitatively assessed the impact of cultural or behavioral differences (e.g., frequent window opening in naturally ventilated Indian offices) on IAQ outcomes.

5. Conclusions

This review demonstrates that combining passive architectural design with affordable, real-time IAQ monitoring systems can reduce indoor pollutants by 25–65%, cut HVAC energy use by 15–35%, and significantly improve occupants' health and productivity.

Practical implications:

1. Architects in India and similar climates should design buildings to be “sensor-ready” from Day 1.
2. Building owners can achieve payback within 2–5 years by using low-cost sensors for demand-controlled ventilation and public IAQ dashboards.
3. Green rating systems (IGBC, GRIHA) and government policies should mandate continuous monitoring of PM_{2.5} and CO₂ in all new commercial and educational buildings by 2030.

Future research directions:

1. Long-term (≥ 2 years) field studies of low-cost sensors' drift in hot-humid Indian conditions;
2. Development of standardized, low-cost field calibration protocols for the Indian context;
3. Investigation of culturally appropriate occupant feedback systems to reduce window-opening conflicts in naturally ventilated offices.

Implementing these steps will transform green buildings into genuine wellness-promoting environments.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Anshul Jain: Conceptualization and writing original draft. Dr. Hridayesh Varma: Supervision, Reviewing the draft.

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