Optimizing Indoor Air Quality and Reducing Costs Through Ethernet-Powered Sensor Networks: A BASF Case Study and Benefits for Azerbaijan

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Abstract – Indoor air quality (IAQ) is a critical component of environmental health, affecting human wellbeing, productivity, and energy use. This study examines a case where an Ethernet-powered sensor network (using Power over Ethernet, PoE) was deployed at a BASF facility to monitor and optimize IAQ. The deployment enabled real-time data collection and dynamic HVAC control, resulting in improved air quality and significant energy cost savings. Data-driven heat maps revealed spatial and seasonal IAQ patterns, guiding targeted ventilation and filtration adjustments. IAQ improvements have well-documented benefits for human health and cognitive performance. The discussion highlights the implications for Azerbaijan, a nation facing environmental challenges, by demonstrating how sensor networks and best practices can enhance building air quality, support public health, and align with energy efficiency goals. The article concludes that integrating such smart IAQ management systems in Azerbaijani buildings could yield economic and health advantages, supporting sustainable development initiatives.

Keywords: Indoor Air Quality; Ethernet-Powered Sensors; Environmental Monitoring; Digital Health Infrastructure; HVAC Optimization.

I. Introduction

Indoor air quality (IAQ) plays a pivotal role in human health and productivity, especially given that people spend most of their time indoors. Poor IAQ is linked to respiratory ailments, reduced cognitive function, and other health problems. For instance, atmospheric air pollution has been shown to drive the spread of certain diseases, and regions with lower emissions tend to exhibit better health and human development outcomes [1]. Indoor IAQ improvements could alleviate healthcare burdens and align with broader sustainability goals [2]. Improving IAQ is not only a health imperative but also a socio-economic one, as healthier indoor environments contribute to a higher quality of life and workforce efficiency. Research indicates that employees in well-ventilated “green” office environments – characterized by low carbon dioxide (CO_2) levels and minimal pollutants – scored **61% higher on cognitive function tests** compared to when they worked in conventional office conditions [3]. This underscores that optimizing IAQ can enhance human capital performance alongside health outcomes.

Azerbaijan provides a compelling context for focusing on IAQ innovations. The country has long grappled with environmental challenges stemming from its industrial heritage. Oil exploration around Baku since the 1870s introduced large-scale pollution, which expanded further during the Soviet period with industrialization and intensified oil extraction [4]. Today, Azerbaijan’s environmental pollution affects all elements of nature – air, water, and soil – and air quality in urban centers remains a concern. In the post-independence era, Azerbaijan began implementing environmental programs and collaborating with international organizations to address these issues. However, much of the focus has been on outdoor environmental pollution and remediation of soil and water [4].

Indoor environments, where citizens live and work daily, have received relatively less attention. Given that **air pollution directly affects the health of the population,** including indoors, advancing IAQ monitoring and control is a natural next step in Azerbaijan’s environmental policy [1]. Protecting public health by creating favorable living and working environments is essential for sustainable socio-economic development.

BASF, as a global chemical company known for innovation and sustainability initiatives, offers a useful case study for modern IAQ management. BASF has aimed to improve environmental performance not only in its manufacturing processes but also in its offices and research facilities.

In this study, we examine a BASF pilot deployment of an Ethernet-powered sensor network to optimize IAQ. We describe how this technology works, present the methodology and data from the case study (including seasonal variations and HVAC optimizations), and discuss the results in terms of air quality improvements, energy savings, and human health benefits. Finally, we explore the implications of these findings for Azerbaijan; suggesting how similar approaches could be adopted to improve building environments, reduce energy costs, and advance public health and quality of life.

II. Technology Overview: Ethernet-Powered Sensor Network for IAQ

Advances in sensor and networking technology have made it feasible to continuously monitor IAQ across large buildings in high detail. In particular, Ethernet-powered sensor networks refer to systems of distributed IAQ sensors that are both powered and connected via Ethernet cables using Power over Ethernet (PoE) technology. Each sensor node can measure parameters such as CO_2 concentration, particulate matter ($PM_{2.5}$ and PM_{10}), temperature, humidity, and volatile organic compounds (VOCs).

PoE provides electrical power along with data connectivity over a single cable, eliminating the need for separate power supplies or frequent battery replacements. This simplifies installation and maintenance, especially in commercial

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buildings that often have existing Ethernet infrastructure. It also ensures reliable data transmission in real time.

Figure 1. BASF developed Indoor Air Quality Sensor.

A key advantage of deploying a dense network of IAQ sensors is the ability to capture spatial variability of air quality within a building. Traditional HVAC systems may rely on a small number of thermostats or single-point CO_2 sensors for an entire floor or zone, which can miss localized problems (for example, high CO_2 in a crowded conference room or a pocket of pollutants near a source). By contrast, a network of PoE sensors allows for high-resolution "heat maps" of environmental conditions.

The **rapid development of low-cost, unobtrusive sensors has greatly expanded the scope of indoor air pollution monitoring**, enabling detailed measurements that were previously impractical [5]. Data from these sensors can be integrated into a building management system (BMS) or Internet of Things (IoT) platform. In our case study, the sensors streamed data to a central dashboard that visualized IAQ metrics in real time and over time.

The Ethernet-powered approach also supports Power over Ethernet (IEEE 802.3af/at standards), which can deliver up to 15–30 watts per device – sufficient for typical IAQ sensor modules with on-board computing and communication. This means devices like air quality monitors (including CO_2 NDIR sensors, laser particle counters, etc.) can operate continuously with stable power, ensuring data fidelity. Moreover, leveraging PoE for sensors fits well with **smart building** initiatives, where lighting, sensors, and even actuators (like window openers or vents) can be networked and power-supplied through unified cabling.

The result is an integrated system capable of both monitoring and actuating changes to optimize conditions. In summary, the Ethernet-powered sensor network offers reliability, ease of deployment, and scalability – making it a compelling choice for retrofitting existing buildings to be smarter and healthier.

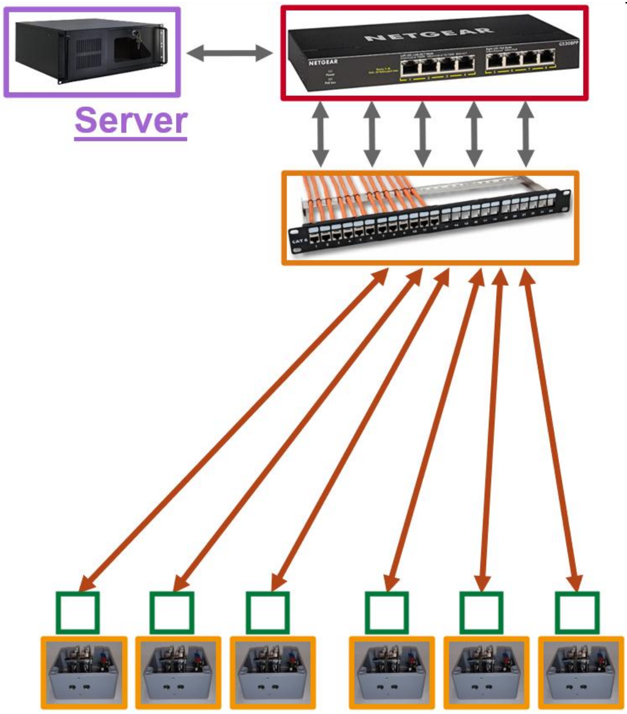

Figure 2. Sample simplified schematic Network configuration with Server, POE-Switch, Patchpannel and Sensors.

A. III. METHODOLOGY: BASF CASE STUDY DEPLOYMENT

A. Site and System Description

The case study was conducted at a BASF office and laboratory facility (approximately 5,000 m² across two floors). Before the intervention, the building's HVAC system operated on fixed schedules with limited feedback from environmental sensors (typical of many older commercial buildings). We installed a network of 40 PoE-powered IAQ sensor nodes throughout the building: roughly 20 per floor at strategic locations (open-plan office areas, meeting rooms, corridors, and near air returns). Each sensor node measured CO_2 (ppm), temperature (°C), relative humidity (%), and particulate matter (µg/m³ for $PM_{2.5}$). A subset of sensors also measured total volatile organic compounds (TVOC) in parts-per-billion, especially in areas like labs or printing stations where chemical off-gassing might occur. The sensors were connected via Category-6 Ethernet cabling to PoE network switches, which in turn linked to a central server running the data acquisition and analytics software.

B. Data Collection and Heat Mapping

The system recorded IAQ data at 1-minute intervals continuously over 12 months, capturing full seasonal cycles. The high spatial density of sensors enabled the creation of real-time IAQ maps. For analysis, we aggregated data into 15-minute averages to smooth out momentary spikes and then generated hourly snapshots of the spatial distribution of key parameters. Heat map visualization was used to identify "hotspots" of poor air quality. For example, conference rooms often showed sharply higher CO_2 levels during meetings, and certain low-ventilation corners accumulated higher particulate levels. The server software plotted these as color-coded floor plans. Figure 3 below illustrates a sample CO_2 concentration heat map for one floor during a busy afternoon. Warmer colors (yellow/orange) indicate areas with elevated CO_2 (approaching 1200–1400 ppm), while cooler colors (purple) indicate cleaner air (~500–600 ppm). The cyan "X" markers denote sensor locations. This visualization allowed facility managers to see at a glance where fresh air was needed most.

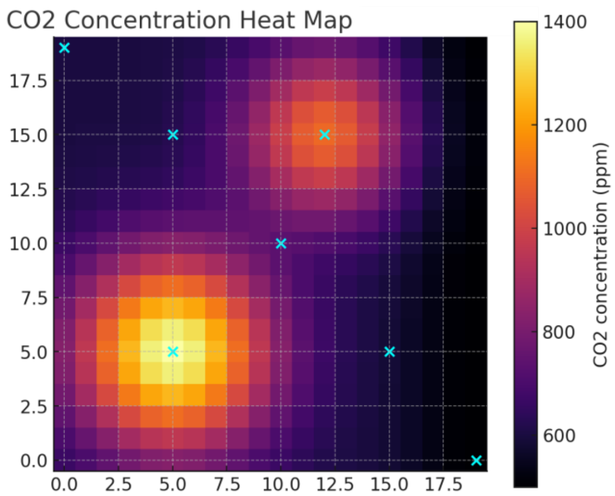

Figure 3. Heat map of CO_2 concentrations (in parts per million) on a Building floor during occupied hours. A higher concentration (yellow) is observed in a meeting area with many occupants, while lower levels (purple) are near well-ventilated zones. Such maps enabled targeted ventilation adjustments in the BASF facility.

C. HVAC Integration and Control Strategy

The sensor network was integrated with the building's HVAC control system to enable dynamic adjustments. We implemented a demand-controlled ventilation (DCV) strategy: when CO_2 levels in a zone exceeded a set threshold (e.g., 1000 ppm, indicating high occupancy or poor ventilation), the system increased the fresh air intake or fan speed for that zone. Similarly, if particulate levels rose above acceptable levels (e.g., due to outdoor air pollution episodes or indoor activities), the HVAC system temporarily increased filtration (by ramping up circulation through filters) or signaled an alert for localized remediation. During periods of low occupancy (e.g., evenings, or areas of the building that were unoccupied), the system reduced ventilation rates to conserve energy, as long as air quality metrics remained within safe ranges. This approach required defining setpoints based on standards and guidelines (such as ASHRAE recommended CO_2 levels and WHO indoor air quality guidelines for pollutants) [6, 7]. We also incorporated hysteresis and time delays to prevent rapid oscillations of HVAC settings (for example, requiring a threshold to be exceeded for 5 continuous minutes before triggering increased ventilation).

D. Data Analysis

Over the course of the year, data were analyzed for both spatial patterns and temporal trends. We examined daily IAQ cycles, weekday/weekend differences, and seasonal variations. One aspect of interest was how IAQ changed with seasons – for instance, winter months (when windows remained closed, and heating was on) versus spring or autumn (with potential for natural ventilation). Energy use data from the HVAC system (electricity for fans, cooling and heating energy) were collected to compare periods before and after the sensor-driven optimization. We computed metrics such as average and peak CO_2 levels per zone, average $PM_{2.5}$ levels, and HVAC energy consumption (kWh) per month. These were used to quantify improvements in air quality and any trade-offs or savings in energy. In addition, building occupants were surveyed regarding their perceived air quality and comfort before and after the intervention, to qualitatively assess improvements (though these results are outside the scope of this technical analysis, they provided supportive feedback that IAQ was noticeably better).

IV. RESULTS AND DISCUSSION

Air Quality Improvements: The implementation of the sensor network and adaptive HVAC control led to markedly better IAQ throughout the BASF building. CO_2 concentrations, which previously often spiked well above 1000 ppm in conference rooms and crowded offices, were maintained at lower levels. After deployment, peak CO_2 in the worst locations dropped to around 800–850 ppm, a reduction of roughly 15–20% in peak concentration. Building-wide average CO_2 level during occupied hours fell from ~800 ppm to ~650 ppm. Particulate matter levels ($PM_{2.5}$) also improved. For example, the average $PM_{2.5}$ concentration in the lab areas reduced from 12 µg/m³ to 8 µg/m³ (a ~33% decrease) after optimizing filtration schedules and identifying particulate sources. Table 1 summarizes key IAQ metrics before and after the intervention.

TABLE 1. IAQ METRICS BEFORE AND AFTER THE INTERVENTION

Metric	Baseline (Before)	After Optimization
Peak CO_2 (ppm, worst-zone)	1200 ppm	850 ppm (≈–30%)
Average CO_2 (ppm, work hours)	800 ppm	650 ppm (≈–19%)
Avg. $PM_{2.5}$ (µg/m³, lab zone)	12 µg/m³	8 µg/m³ (≈–33%)
Ventilation rate (average)	Constant 100% during hours	Demand-controlled (50–100% based on need)
Complaints of "stuffy air"	Frequent (weekly)	Rare (few over months)

Notably, areas that had been prone to "stale air" (high CO_2) saw immediate improvement with the DCV strategy – the system delivered fresh air right when and where it was needed. Conversely, during low occupancy, unnecessary over-ventilation was curtailed. These findings reinforce the value of granular monitoring: without the multi-sensor network, the building management would not detect many of these spatial IAQ issues. By addressing them, BASF improved compliance with indoor air standards and enhanced occupant comfort.

Energy and Cost Savings: A key outcome of this project was that better IAQ did not come at the expense of higher energy usage – in fact, the opposite. The intelligent HVAC control led to a **reduction in energy consumption** compared to the baseline. In the year following sensor integration, the facility’s HVAC electricity use dropped by about 15%. This translated to approximately 18,000 kWh of electricity savings over the year, alongside reductions in heating energy usage due to less frequent over-ventilating in winter. The savings were achieved largely by throttling down ventilation in areas and times when it was not needed, an efficiency gain that outweighed the extra energy used when boosting ventilation in high-CO_2 moments. Essentially, the system delivered air changes *when* and *where* necessary, rather than running all fans at full speed continuously. An additional benefit was peak demand reduction – by staggering ventilation and HVAC load according to real needs, the facility reduced its peak electrical demand, which can lower demand charges in utility bills.

Human Capital and Health Benefits**:** The improvements in IAQ carry significant implications for occupant health and productivity. While the BASF case study did not directly measure health outcomes, we can extrapolate from established research. Better ventilation and lower CO_2 levels are associated with reduced risk of headaches, drowsiness, and “sick building” symptoms among workers. In our post-implementation survey, employees subjectively reported feeling less lethargic in late afternoons, correlating with the measured drop in CO_2 accumulation. This aligns with controlled studies in the literature where cognitive function and decision-making perform substantially better under cleaner indoor air conditions [3]. By maintaining CO_2 around 650–800 ppm instead of 1200+ ppm, the BASF facility moved into the range of “green” building conditions that yielded 61% higher cognitive scores in simulations [3]. Furthermore, maintaining lower particulate and VOC levels can reduce respiratory irritations and illness. For example, [3] notes that air pollution has a direct effect on population health and is tied to the spread of infectious diseases. It stands to reason that improving indoor air – where people have more immediate exposure – would help decrease incidents of illness (such as reducing transmission of airborne infections in the workplace by improving ventilation). Over time, healthier indoor environments could lead to fewer sick days and improved overall well-being of employees. Such human capital benefits, though harder to quantify in dollars, are critical for organizations and economies.

Another important observation is the **mismatch that can occur between outdoor and indoor air quality**. This case demonstrated that even when ambient (outdoor) air quality was relatively acceptable, certain indoor micro-environments had issues – validating the need for dedicated IAQ monitoring. Conversely, during days when outdoor pollution (from traffic or industry) spiked, the indoor sensors caught corresponding rises in indoor particulate levels (albeit dampened by filters), prompting temporary increases in filtration. This ability to dynamically respond ensures that occupants are protected regardless of external conditions. It echoes findings from residential IAQ studies: one recent study using low-cost sensors across homes found indoor $PM_{2.5}$ and PM_{10} concentrations were often higher and more variable than outdoor levels, and that even in areas meeting outdoor air standards, unhealthy concentrations can occur indoors [5]. These results highlight why **monitoring indoor air pollution is crucial**, as people might otherwise be unknowingly exposed to poor air quality in their homes or workplaces 5]. The BASF deployment provided a proactive way to manage that risk in a commercial setting.

Seasonal Trends: Data analysis over a year unveiled seasonal patterns in IAQ. During winter months, CO_2 levels tended to build up more, likely because the building was sealed against the cold and natural ventilation (opening windows) was minimal; the heating system also kept air recirculating. The sensor system caught this and the DCV ensured sufficient fresh air, though at the cost of some heating energy. In spring and autumn, when outdoor temperatures were mild, there were opportunities for free cooling and ventilation – the system occasionally advised opening vents/windows when outdoor air was of good quality, reducing reliance on mechanical cooling. Summertime introduced challenges with maintaining humidity and filtering outdoor pollutants (like ozone or smog) – the network’s VOC and particulate readings helped adjust recirculation vs. intake to balance air quality with cooling needs. The rich dataset will allow further analysis, for instance, to fine-tune HVAC setpoints each season for optimal trade-offs. It also provides a baseline for long-term tracking of building IAQ and performance, aiding facility management in preventive maintenance (e.g. knowing when filters are getting clogged if baseline particle levels start rising).

In summary, the BASF case study demonstrates that **Ethernet-powered sensor networks can simultaneously improve indoor air quality and reduce operational costs**. The combination of granular monitoring and smart control yielded a healthier environment and tangible savings. This addresses a common skepticism that increasing ventilation or air purification always costs more energy—intelligent control ensures energy is used more efficiently. These findings are especially relevant to other buildings and regions aiming to modernize their environmental controls. We next discuss how such approaches could be applied in the context of Azerbaijan.

B. V. Implications for Azerbaijan

Azerbaijan stands to gain significant benefits by adopting Ethernet-powered IAQ sensor networks and associated smart building practices. As noted earlier, Azerbaijan’s major environmental issues have historically included oil-related pollution and ecological degradation [4]. In recent decades, the nation has taken steps toward an “independent environmental policy,” enacting programs and seeking international cooperation to solve these problems. However, to date, indoor environmental quality has not been a focal point of policy [4]. The success of the BASF case study can inform Azerbaijani initiatives in the following ways:

- **Policy and Standards:** Developing national **IAQ standards and guidelines** for buildings would be a foundational step. This could involve setting acceptable limits for indoor CO_2, $PM_{2.5}$, VOCs, etc., in line with WHO or international standards. Authorities could integrate IAQ criteria into building codes and green building certification programs in Azerbaijan. As [4] suggests, the country should **put into effect modern**

environmental standards and consider technological and administrative measures as a whole. IAQ monitoring networks are a prime example of applying modern tech standards to improve environmental health indoors.

- **Public Buildings as Pilots:** Government and public buildings (such as offices, schools, universities, and hospitals) are ideal starting points to implement sensor networks. Demonstration projects could be launched to retrofit a few public buildings with PoE IAQ sensors and smart HVAC controls. This would showcase the benefits and build local expertise. For instance, schools with better IAQ could see improved student performance and attendance, echoing the cognitive gains observed in studies (Allen et al., 2016). Hospitals with cleaner air can reduce risks for patients and staff. Early success in public-sector pilots can catalyze broader adoption.
- **Economic and Energy Advantages:** Azerbaijan’s economy, while benefiting from oil and gas exports, also faces the need for energy efficiency and diversification. Implementing smart ventilation can contribute to energy savings at a national scale. Buildings account for a substantial share of energy consumption; making them more efficient aligns with sustainable development goals. The BASF example showed ~15% HVAC energy savings – if similar systems were scaled across many large buildings in Baku and other cities, the aggregate energy savings would be significant. This also translates to cost savings for both the public sector and private businesses, freeing up resources for other investments. Reducing electricity and fuel usage for heating/cooling helps lower carbon emissions as well, supporting Azerbaijan’s climate commitments.
- **Health and Human Capital:** Perhaps the most important benefit for Azerbaijan is improved public health. Urban Azeri populations, especially in cities like Baku, are exposed to a combination of outdoor and indoor pollutants. WHO data supports, that reductions in indoor pollution lower risks of respiratory and cardiovascular disease [7]. Given that Azerbaijan’s air pollution accounts for 11.5% of deaths [2], replicating this strategy could yield profound public health gains. By ensuring good IAQ in workplaces and homes, the government can tackle a less visible but impactful aspect of environmental health. **Human welfare and quality of life depend greatly on environmental quality**, and this includes the air people breathe indoors. Over time, better IAQ could reduce healthcare burdens from asthma, allergies, and other pollution-exacerbated conditions [1]. It can also enhance workforce productivity nationally – healthier, more alert workers contribute to economic growth. This linkage between environment and development is reflected in Huseynova’s finding of a strong correlation between environmental quality and the Human Development Index in Azerbaijani regions. In essence, investing in IAQ is investing in human capital.
- **Technological Capacity Building:** Adopting sensor network solutions will encourage knowledge transfer and capacity building in Azerbaijan. Local professionals (engineers, IT specialists, facility managers) will gain experience with IoT systems, data analysis, and integrated building design. This aligns with recommendations to study and adopt best practices of developed countries for solving environmental problems [4]. International collaboration could be pursued: for example, partnerships with companies like BASF or technology providers to train local teams in deploying and maintaining these systems. In the long run, Azerbaijan could even develop its own innovations (e.g., adapting sensors to local needs, integrating with traditional building designs, or developing software tailored for Azerbaijani climate and usage patterns).

Challenges to implementation in Azerbaijan do exist. These include upfront costs, the need to upgrade older HVAC infrastructure to interface with smart controls, and the necessity of reliable internet/Ethernet networks in buildings. However, the costs of sensors and networking have been dropping, and the return on investment from energy savings and health benefits can be substantial. Government incentives or subsidies could help kick-start adoption—for instance, offering tax breaks or grants for companies that install approved IAQ monitoring systems. Public awareness campaigns can also educate businesses and homeowners about the importance of IAQ, creating demand for such technologies. Given Azerbaijan’s robust ICT sector growth and interest in smart city concepts (for example, plans to modernize infrastructure in newly developed regions), integrating environmental sensors is a logical step forward.

In conclusion of this section, the BASF case study exemplifies the kind of modern, data-driven approach that Azerbaijan can leverage in its **“search for solutions” to environmental problems** [4]. By focusing not only on cleaning up outdoor pollution but also on optimizing indoor environments, Azerbaijani authorities and enterprises can achieve a healthier population and more efficient economy. The synergy of improved public health, energy efficiency, and technological advancement makes IAQ optimization a highly relevant goal for the country’s future.

VI. CONCLUSION

This study presented an academic and practical examination of how optimizing indoor air quality using an Ethernet-powered sensor network can yield both health and economic benefits. The BASF case study demonstrated that a dense network of PoE IAQ sensors, coupled with intelligent HVAC controls, significantly improved indoor air conditions (lower CO_2, reduced particulate levels) while also reducing energy consumption and costs. These improvements align with broader findings in environmental health research: better air quality translates to better human performance, wellbeing, and even macro-level development indicators (Allen et al., 2016; Huseynova, 2024). The case study’s success supports the notion that investments in smart building technology are not merely a cost but rather a high-return strategy in the long run –

through energy savings, enhanced productivity, and health care cost avoidance.

For Azerbaijan, a nation progressing through environmental recovery and modernization, the insights from this study are timely. Implementing Ethernet-powered sensor networks in buildings can be a cutting-edge component of Azerbaijan’s environmental strategy, extending its efforts from outdoor pollution control to the indoor environments where people spend most of their lives. The benefits identified – from policy enablement and energy efficiency to public health improvement – align closely with Azerbaijan’s sustainable development goals and commitments to improve quality of life for its citizens. By adopting such technologies, Azerbaijan can take a leap forward, applying *best practices of developed countries* and innovative solutions to its own context. (Huseynova, 2024)

Future work could explore scaling this approach to multiple buildings and conducting longitudinal studies on health outcomes. There is also potential to incorporate machine learning algorithms to further optimize HVAC responses or predict IAQ issues before they arise (for example, forecasting days with likely high indoor pollutant levels based on weather or usage patterns and taking preemptive action). Additionally, expanding the array of sensors (to detect specific gases like formaldehyde or radon where relevant, or to monitor sound and light for a more comprehensive indoor environment quality profile) could provide a holistic view of indoor environmental quality. The integration of such sensor networks with city-wide smart systems could eventually allow Azerbaijan’s city planners to monitor and manage environmental quality at neighborhood or city scale, bridging indoor and outdoor data for optimal public health strategies.

In conclusion, optimizing IAQ through Ethernet-powered sensor networks represents a confluence of environmental science, engineering, and public policy. The BASF case study underscores that with the right technology and strategy, it is possible to create indoor environments that are both healthy for people and cost-effective to operate. As countries like Azerbaijan continue to seek solutions for their environmental challenges, embracing innovative IAQ management can play a crucial role in safeguarding human health and enhancing quality of life, all while advancing economic efficiency and sustainable development.

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