Decoding ‘Fresh Indoor Air’: Exploring technologies and design interventions to achieve ‘a fresh breath’ in urban indoor spaces

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Abstract. This paper addresses the common dilemma in every contemporary city-dweller’s life: One cannot let outdoor air come into indoor spaces due to high pollution (especially in winter months); yet we need outdoor air to balance the O_2 and CO_2 inside our building and flush out the indoor contaminants. The concept of ‘freshness’ of indoor air itself is explored in depth beyond the limited purview of ‘particulate pollutants’ only. Developing on the fact, that the best indoor air needs to replicate the qualitative aspects of the air we find in nature: amongst thick woods or by a gurgling stream; the paper touches on how to recreate the physical, chemical as well as electrical properties of natural air in our indoor environments. The toxicological impacts of impure indoor air on human body are established and their relation to the health, sense of wellbeing and human productivity is studied alongside.

The technologies and design interventions that can address aforementioned concerns of ‘polluted indoor air’, range from highly technical to some purely common sensical solutions. Also, the perception and practice of ‘ventilating indoor spaces’ is closely linked to the fundamental understanding of need for ‘fresh indoor air’ by users. Hence the dynamics of indoor air change need to be integrated holistically. The ‘urban bane’ of ‘polluted indoor air’ is studied with a look at some cutting-edge solutions for addressing the same, especially in context of composite climate, urban lifestyle and evolving social psyche of our cities.

Keywords: Fresh indoor air, indoor air pollutants, CO_2 balance, urban bane, indoor fresh air strategies

1. The challenge of ‘indoor air quality’ in urban context

The focus of this paper is threefold; firstly to decode the prevalent challenge of indoor air quality in urban and semi-urban cities (especially in India) falling under composite climate; secondly, to understand the concept of indoor air quality holistically in context of human wellbeing; and thirdly to explore possible solutions to achieve ‘fresh indoor air’.

We, the urban earthlings, have surrounded ourselves with environments our bodies, our cells, our DNA and our energy fields are finding hard to align with. In context of subject under consideration, there are four key aspects of our lifestyle and built environments that need a closer scrutiny:

a) We are constantly exposed to numerous chemicals, by way of lifestyle products, construction finishes and materials, cosmetics, pesticides etc., all of which are impacting the air that we breathe (especially in indoor spaces).
b) An average human being spends more than 90% of his life indoors, so indoor air quality becomes very relevant for health.
c) In case of chronic patients, even minuscule concentration levels of air pollutants can trigger or aggravate the disease. More important is the fact that the concentration levels that can be harmful to human health are beyond the 'odor threshold' and therefore undetectable.
d) There are no legally binding exposure limits for residential indoor air which further pushes it down the 'list of achievable' in most design narratives.

Indian cities are facing the problem of severe air pollution. As per 2018 study of world's most polluted cities [1], twenty out of twenty five world's most polluted cities are in India. The national capital region (NCR) of India, consisting of Delhi along with the satellite towns of Faridabad, Noida, Gurugram and Ghaziabad presents an apt case to study this phenomenon. NCR experiences four months of extreme summer (usually starting in mid-March till June) followed with few months of rains and high humidity and little over two months of extreme winters (starting mid-December till end February). The headlines, especially in months of October and November, are replete with news about deteriorating outdoor air quality.

While outdoor air quality comes under mass scrutiny, little attention is given to the 'indoor air quality'. For most people, a knee jerk reaction to secure indoor air quality involves closing all openings of the building (to prevent ingress of polluted outdoor air), deploying expensive indoor air purifiers or keeping potted indoor plants. Often such measures remain insufficient since the indoor air quality of any building, besides being directly influenced by the outdoor air quality, is also greatly influenced by the lifestyle patterns (impacting the usage of space and ventilation strategy), ambient temperature; the building envelope, indoor materiality and finishes, chemicals that are used indoors etc.

1.1 Components of 'Fresh Indoor Air' and understanding good 'IAQ'

As per the Environmental Protection Agency (EPA), indoor air quality (IAQ) refers to the "air quality within and around buildings and structures, especially it relates to the health and comfort of building occupants". The ASHRAE defines IAQ as: "Air in which there are no known contaminants at harmful concentrations as determined by authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction". Simply put, air pollution refers to the presence of gaseous and solid components in the air that disturb the natural composition of air and become cause of health problems to life forms. Pollutants in the indoor air can be divided into the following categories:

- Volatile organic compounds & Semi-volatile organic compounds (VOCs)
- Radon (also any other radioactive nuclides)
- Fibers, particulate matter (commonly known as PM2.5 and PM10)
- Microbes and molds (fungi and yeast)
- Sulfur dioxide, nitric oxides, hydrocarbons (which percolate indoors in high traffic localities)

Besides aforementioned pollutants, there are few 'lesser known' aspects of indoor air quality whose imbalance can create immense detrimental impact on quality of human life, besides the pollutants. These include:

a) Balance of oxygen and carbon-di-oxide
b) Balance of carbon monoxide
c) Balance of negative and positive ions
d) Balance of humidity and temperature
e) Balance of electrostatic field
f) Balance of electromagnetic radiation

Of the aforementioned, good air quality is only equated with low (permissible) levels of particulate matter. All other pollutants and balance criterion seldom find place into design consideration. Yet the fact remains that almost all the aforementioned aspects (pollutants and other qualities of air) display immense interdependence as they impact each other in a very complex yet distinct manner in adding to indoor air pollution.

Fresh indoor air can be defined as one that possesses all the characteristics (and the qualitative balance) of air that is found in natural environs (like vicinity of a gurgling spring or in midst of woods). Quantitatively, it maybe reasonably accurate to define fresh indoor air as one having following characteristics [2]:

1. $CO_2 < 600$ ppm
2. $O_2 > 20\%$
3. Particulate matter (PM 2.5 <25µg/m^3 daily mean, and PM 10<50µg/m^3)
4. Number of air ions (negative and positive) > 500 nos./cm^3
5. Total volatile contents (TVOCs) < 300 µg/m^3
6. Formaldehyde concentration < 50 µg/m^3
7. Relative Humidity - 40% to 60% (indoor temperature range of 22ºC to 26ºC)
8. Static electricity – 100-500 V/m

In general, all aforementioned qualitative aspects of good indoor air can be achieved with good ventilation of an indoor space (usually .5 air changes per hour in homes and offices suffice for general ventilation needs) provided outside air is clean; which is seldom the case in current urban cities. For purpose of this paper, we shall be focusing on dynamics of achieving O_2 and CO_2 balance and controlling levels of particulate matter and strategies addressing same.

1.2 ‘Toxicology of polluted indoor air’

Indoor air quality figures among top five risks to human health (as per EPA). This is due to the fact that indoor air often contains many times more contaminants than outside air. Ample medical research is available showing that polluted air is the cause of major health problems including acute and chronic diseases, lowered immune response, higher susceptibility to infectious diseases, lower life expectancy, as well as mental disorders.

For a balanced perspective on the impact of indoor air pollution, it is critical to understand the limits of current body of scientific knowledge as regards to the environmental toxicological evaluations. There are so many chemicals being added to our environment and our lifestyle every day that it is not possible to evaluate each one for their toxicological impact. Furthermore, even when the toxicological evaluations for certain pollutants are known, the ‘simultaneous and cumulative impact’ of a number of such pollutants on human body is never studied. This is also the reason that many diseases cannot be pinned to a particular pollutant because our bodies respond to the ‘cumulative pollutant load’ and never to pollutants individually, as is the case during testing and evaluation process.

Since the 1950s, new disease patterns have emerged that are associated with increasing levels of outdoor and indoor air pollution. These are commonly understood as following:

- SBS (**S**ick **B**uilding **S**yndrome) [3]
- CFS (**C**hronic **F**atigue **S**yndrome) [4]
- MCS (**M**ultiple **C**hemical **S**ensitivity) [5]

Of the aforementioned, sick building syndrome (SBS) is a disease pattern that can be directly linked with indoor air pollution. When indoor air pollutants cause allergies and many complex and nonspecific symptoms as well as irritations of the mucous membranes and eyes, these are commonly attributed as SBS. In most cases of SBS, besides the chemical trigger, HVAC system of the building has also been known to play a deterministic role.

1.3 Indoor air quality and productivity

Bad indoor air can make people fall sick, thus increasing sick leaves and decreasing performance and sense of wellbeing and thereby adversely impacting the productivity of residents. On the other hand, good IAQ or ‘fresh indoor air’ induces a sense of well-being, enhanced immunity and good blood circulation, low stress and better concentration, easy breathing and better oxygen intake, good physical and mental health, comfort, motivation to perform and give best; thereby increasing productivity and performance (with reduced sick leaves and attrition rate).

Focus on IAQ, therefore becomes a key design determinant for any good space and built-environment design. It is evident that human well-being and vitality, both physical and mental, improve with improved indoor air quality.

A study carried out in 2012 at Department of Energy's Lawrence Berkeley National Laboratory [6],found “statistically significant and meaningful reductions in decisionmaking performance” in test subjects as CO_2 levels rose from a baseline of 600 parts per million (ppm) to 1000 ppm and 2500 ppm (see Fig.1)

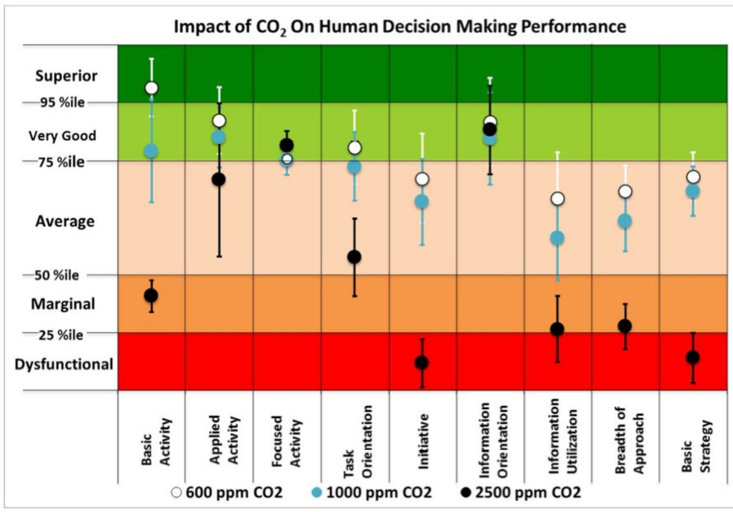

Fig. 1. Impact of CO_2 on human cognitive abilities [6]

Another study done at the Harvard T.H. Chan School of Public Health[7] in 2016 concluded that ‘Exposure to CO_2 and VOCs at levels found in conventional office buildings was associated with lower cognitive scores than those associated with levels of these compounds found in a Green building or Green+ buildings with higher oxygen component and lower CO_2 and VOC components (see Fig.2)

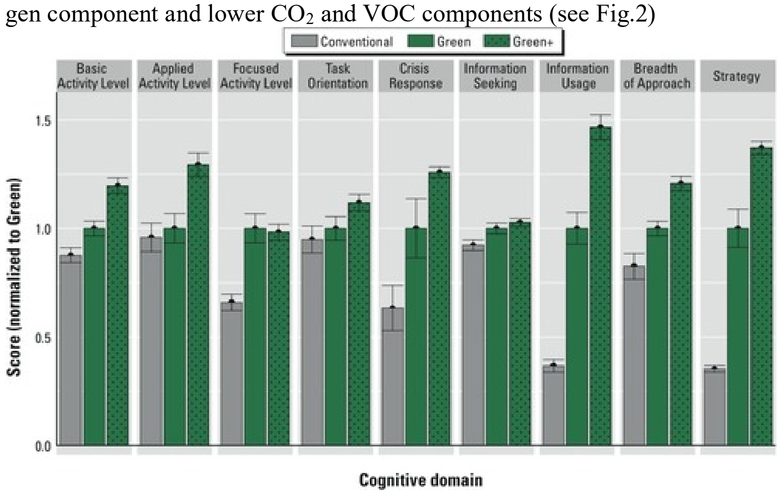

Fig. 2. Impact of CO_2 on workplace productivity parameters [7]

This study has an important takeaway for workplace efficiency as stated in it's findings: Increasing the supply of outdoor air lowers ~~exposures~~ to not only CO_2 and VOCs but also to other indoor contaminants. [7]

Productivity and innovation are the key concerns for any strategic framework of an organization. Yet the boardroom narratives on productivity growth seldom look towards the oxygen vs carbon-di-oxide balance of the workspace as a suspect for low performance of teams. An extremely high level of CO_2 is commonly observed at clinics, gymnasiums, workplaces and even institutions that deploy split air conditioning units (wall mounted type without any fresh air intake provision). Such spaces remain closed for weeks together with no exchange of fresh air thereby leading to 'stale but cool' indoor conditions. Many offices in IT parks, malls in commercial hubs and restaurants in market place have centralized air conditioning, however, the fresh air (oxygen) mix that happens at the air handling units (AHUs) and outdoor air intake programmed at the treated fresh air (TFA) units is seldom monitored by the users. It is not uncommon that to save energy in peak summer season, the facility managers are instructed to reduce the fresh air intakes (of heated outdoor air). Such practice again leads to sub-optimal quantity of oxygen in enclosed spaces. While energy maybe saved but such benefits come at the cost of productive and cognitive efficiency of users.

The fact that contemporary architecture treats air-conditioned spaces as 'permanently sealed boxes' adds to the challenge. Due to inability of the space (with fixed or no windows) to breathe (ventilate) naturally, even during benevolent weather months, such buildings do not get any fresh air.

Such design practices, of creating more and more boxed and air-conditioned spaces, can be attributed to two extremities that an urban dweller experience (especially in National Capital Region of India). First is the extreme climate (both hot and cold) and second being excessively polluted outdoor air (often Air Quality Index value exceeding 400). This leads to the common dilemma in every contemporary city-dweller's life: One cannot let outdoor air come into indoor spaces due to high pollution levels (especially during winter months); yet we need outdoor air to balance the O_2 and CO_2 inside our building and flush out the indoor contaminants.

1.4 Indoor air and the balance of Oxygen and Carbon-di-oxide

Main source of CO_2 generation in any enclosed space is breathing, which causes oxygen levels to decrease simultaneously. Fresh air contains about 21% oxygen and 0.04% carbon dioxide. The exhaled air contains about 16% oxygen and 4% carbon dioxide. When the O_2 and CO_2 ratio nears 20% oxygen and 0.07% carbon dioxide, the first ill effects start manifesting which include tiredness, poor performance, headaches, and an increased breathing rate. Next labored breathing sets in and eventually leads to suffocation at 15% oxygen and 5.4% carbon dioxide. The brain cells are the first to be adversely affected by a lack of oxygen and an excess of carbon dioxide. Hence CO_2 level of 0.07% (700 ppm or parts per million) should not be exceeded on a long term basis. However, in most urban areas, it is challenging to keep carbon dioxide levels of the indoor air below 700 ppm on a permanent basis owing to the fact that outdoor pollution makes people shut the windows.

2 Ventilation and indoor air quality

Another conclusion of the study done by Harvard T.H. Chan School of Public Health[7], was that a continuous supply of fresh air keeps the level of CO2, and CO in the air under control, which is very critical for the optimum performance of human body and mind. We all know this phenomenon as 'ventilation' and it is measured in terms of 'air exchange per hour'(ACH) for any enclosed space. Generally, the air exchange rate is a good indicator of the overall indoor air quality, however it varies based on the number of occupants and their nature of activity levels.

Ventilation of indoor spaces is of two kinds. Forced or controlled ventilation (via mechanical means) and natural ventilation or convective air movement (via suitably sized and located windows, ventilators and doors). In this paper, we focus on natural ventilation aspects as therein lies a large potential to achieve good indoor air quality without energy consumption.

Generally, in an enclosed space (with closed windows and doors), the air exchange rate varies between 0.2 and 0.5 m^3/h, by means of air exchange from door and window rebates, joints, cracks etc. As an example, in a typical bedroom of size 3.5m X 5.5m X 2.8m (approx.54m^3) with three occupants and no ventilation, the carbon dioxide level of the air increased within four hours to [8]

- 0.30 % (3000 ppm) at 0.3 air change per hour (ACH)- non ventilated
- 0.15 % (1500 ppm) at 1.0 (ACH)- door opened occasionally
- 0.09 % (900 ppm) at 2.0 (ACH)- with nominal ventilation

After eight hours of sleep, CO_2 levels in poorly ventilated bedrooms frequently exceed 3000 ppm [8]. Therefore, sufficient natural ventilation, that can maintain carbon dioxide levels below 0.07% or 700 ppm is a prerequisite for healthy indoor air, especially in airtight buildings. Natural ventilation is essentially air movement caused due to temperature and pressure difference between outdoor and indoor. Faster ventilation happens when openings are placed across the room and when the outdoor and indoor temperature differential (gradient) is more or faster air exchange happens in extreme weather conditions.

Low temperature difference = low air pressure gradient = slow air change (during moderate weather)

High temperature difference = high air pressure gradient = fast air change (during extreme weather)

As a thumb rule, for a wide window in a bedroom (as aforementioned) one complete air change would usually take following duration in different seasons:

1. Moderate season (spring, autumn): 25-30 minutes
2. Extreme winter or summer: 6-10 minutes

2.1 Ventilation and Energy loss

In composite climates, substantial energy is expended during cold and warm seasons to keep indoor air temperature and humidity within comfortable range. Natural ventilation during extreme weather conditions can cause a lot of 'energy bleed' if windows are opened to facilitate natural ventilation as required. This poses a unique challenge in urban areas with composite climate. Under such situations, natural ventilation with wide open windows and doors for a 'limited period of time' is always preferable instead of continuous ventilation so that air exchange happens quickly without much loss of inside 'coolth' or 'warmth' and energy can be preserved.

Some recent innovations, however, have facilitated the possibility of natural ventilation without much energy loss and maintain a good indoor air quality even when outdoor pollution is very high.

3 New age strategies to achieve fresh indoor air

3.1 Ventilation with trickle and flap vents (manual and automated)

Trickle or flap vents are small slits that facilitate air movement. These are usually installed in the upper frame of any window but can even be designed on the sides as per demand of design. Many Europe based manufacturers of such products have started marketing in India.

Some low end models of flap vents of some companies [9] offer a manual control, filter enabled, weather and inset proof slit vents. These profiles can be attached to any kind of new or installed window frames. (see fig.3)

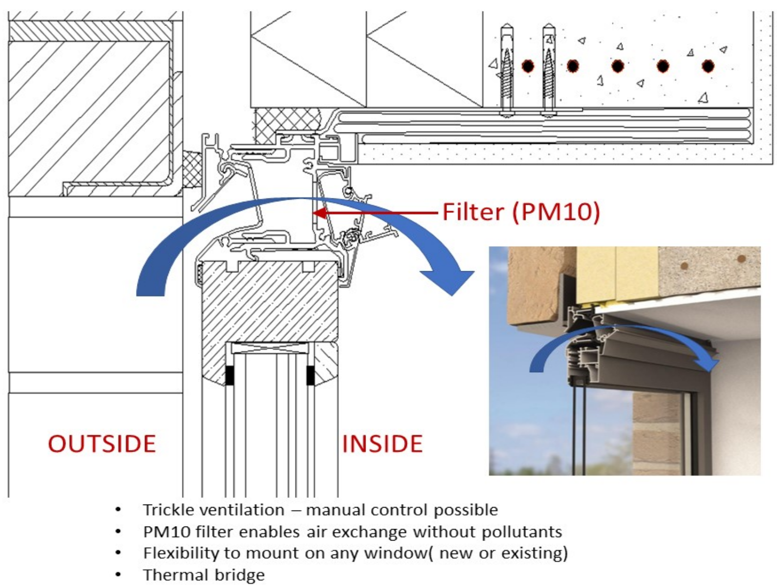

Fig. 3. Flap vent mounted on upper frame; manual operation [9]

With the high end models, there are possibilities to have automated sound-insulated flap vents with inbuilt axial fans that push in outdoor air. These fans are actuated automatically when indoor CO_2 levels cross the preset limits (detected through demand control sensors) and opens the vent to let in outside air till optimal CO_2 levels are achieved indoors. The inbuilt PM10 filters restrict passage of outdoor pollutants. The filter can be cleaned and reinstalled periodically and in more advanced models, heat exchange option is also possible to further minimize energy losses that could be caused due to ventilation. (see fig.4)

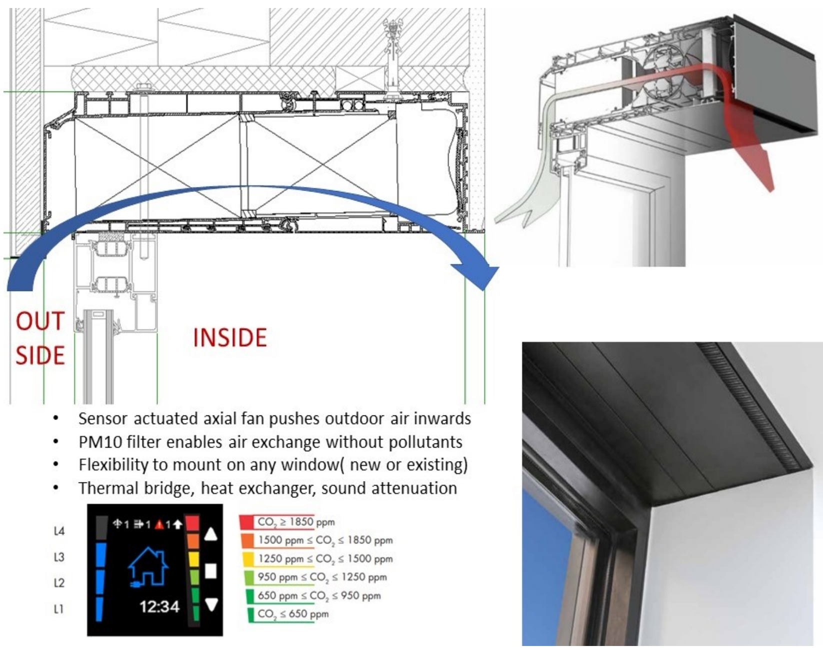

Fig. 4. Automated forced ductless window frame integrated ventilation [9]

With use of such solutions, indoor O_2 and CO_2 balance is maintained with minimal energy loss regardless of outdoor pollution levels. The applied cost of such solutions works out to be a fraction of the total fenestration budget. Considering the health benefits of these ductless fresh indoor air systems, such innovations payback their capital costs over a short period of time.

3.2 Nano-fiber based pollution nets

Since PM2.5 and PM10 pollutants are of key concern (besides the noxious gases), nano-fabric enabled window mesh offers an innovative solution. While carbon and polymer based nano-fabrics have been around for some time now, recently an indigenous team of IIT-Delhi [10] has developed a multi layered mesh which can be installed on any window in place of conventional window nets (insect mesh) on all operable fenestrations. The outer layer of this mesh is hydrophobic, which repels water and makes it water-resistant, providing protection against light-showers, yet retaining the structural strength expected of an insect mesh. It's installation ensures free ingress of outdoor air (without pressure drop) while filtering out pollutants up to PM2.5 size. No special attachment of interface is needed and the window (new or existing) operates in conventional manner. (see Fig.5)

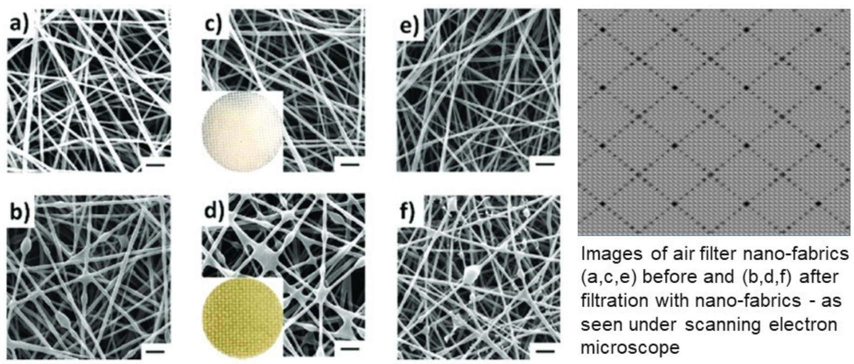

Fig. 5. Nano fabric based pollution nets [11]

Usually window area in average building is approximately 40%-50% of total wall area and out of this 50% area is operable where such nano-filter net can be applied. Effective application of such simple innovations offers an extremely cost-effective way to achieve fresh indoor air.

Aforementioned solutions are especially relevant considering that these can be applied to both green-field as well as brown-field projects (also address retrofitting needs) and be effective in all kinds of climatic environments.

4. Conclusion

Architecture developed as man's response to protect himself from forces of nature and other dangers that prevailed. Today, with the advent of 'pollution age', the nature of dangers that threaten the well being of mankind has changed it's form and source. Consequently, technological innovations and their appropriate integration in architectural design and construction detail holds the key to achieve fresh indoor air quality.

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