

# CLEARING THE AIR

Multi-functional  
technology to maintain  
indoor air quality



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## EXECUTIVE SUMMARY

Most of modern life is lived indoors. With the COVID-19 pandemic restricting large physical gatherings, the time we spend indoors has increased even more. But being indoors isn't an escape from air pollution. In fact, it can be the opposite, with indoor air quality (IAQ) being sometimes worse than outdoor air pollution due to the effects of air pollutants from both indoor and outdoor sources.

Studies have revealed that poor air quality has adverse health effects, highlighting the rising need for indoor air quality technology. Existing IAQ maintenance technology focuses on three strategies: controlling the source of the pollution, keeping up air ventilation, and cleaning the air. However well these technologies have served us, there are drawbacks too: such as the high maintenance and energy costs it takes to run these air cleaning systems.

The growing IAQ market is an opportunity-filled one, driven by increasing global awareness and demand for good indoor air quality. Identifying the need to maintain clean air indoors, this white paper presents an overview of current and advancing technologies that will help improve indoor air quality. Our paper also identifies market and technology needs relevant to the key players across the IAQ value chain. We analyse state-of-the-art technologies and emerging innovations from the patent landscape to identify potential challenges, advances, and opportunities for new innovations to fill the gaps.

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## Key highlights

### 01

#### Consumer and regulatory demands drive the development of IAQ technology

As awareness regarding the importance of good indoor air quality grows, so does the demand for portable and commercial air cleaning systems. The need for better IAQ technology is also driven by rising regulations on green building practices, which include standards for indoor environment and air quality. Green building regulations are a growing trend across the world, especially in emerging markets like Indonesia, Vietnam and the Philippines.

### 02

#### Opportunities abound in the IAQ market

The IAQ market is forecasted to grow by US\$9.5 billion by the end of 2024 and opportunities exist for key players all along the IAQ value chain, spanning the manufacture and supply of raw materials and components, air purification system manufacturers and system integrators, monitoring and maintenance solutions as well as regulation and certification. IAQ will remain a key consideration in the residential, commercial, industrial and transport sectors, with extra potential adjacent markets in other applications such as food logistics and agriculture.

### 03

#### IAQ technology is advancing air cleaning methods

Air cleaning has been proven to effectively complement source control and ventilation strategies in maintaining good IAQ. With different pollutants requiring different air cleaning technologies, advances in air cleaning dominate the technological development in the IAQ market, most notably broad-spectrum innovations in filtration technology, catalytic oxidation and biological methods.

### 04

#### Innovations in air cleaning materials continue to increase

In the mature market of filtration, innovations focus on improving the performance, functionality and energy efficiency of existing filter technologies. Research on catalytic oxidation, which is gaining traction for indoor air purification, is shifting away from photocatalysis to allow less costly systems that can operate in the absence of light. Last but not least, though still emerging, biological methods are also being developed to tackle biological contaminants and volatile organic compounds (VOCs).

### 05

#### Combination is key

Maintaining good IAQ is a complex challenge that requires balancing effectiveness with energy efficiency as well as identifying the best solutions for the many different types of air pollutants. There are opportunities to explore combined strategies in air cleaning, as no current or advancing method can deal with the varied quality of the pollutants that make up air pollution. Technologies that can unify multiple strategies to optimise air cleaning while reducing energy cost will be in demand.



# THE PROBLEM: THE NEED FOR CLEAN INDOOR AIR

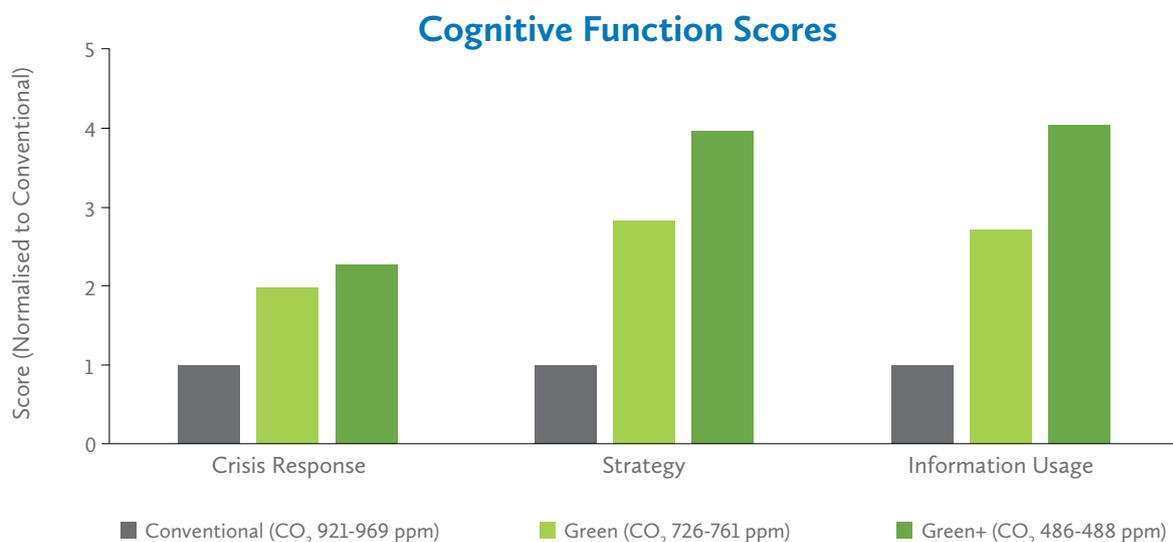
It's easy to take the air we breathe for granted, especially when we're indoors. With air quality governing bodies such as the World Health Organisation (WHO) and Environmental Protection Agency routinely publishing the status of air pollution, most of us are aware that rapid urbanisation and industrialisation has led to deteriorating air quality outdoors. But what people may not be aware of is that outdoor air pollution affects the quality of the air indoors as well.

In a world where we spend about 90% of our time indoors, the need for good air indoors is significant. However, the air indoors can be up to five times more polluted than outdoors<sup>1</sup>. Though invisible and often

ignored, poor indoor air quality can have a profound impact on human health. The effects of poor air quality do not always make themselves known immediately, but studies have shown that poor air quality nonetheless has significant effects.

In fact, ambient and household air pollution is responsible for seven million premature deaths each year<sup>2</sup>. Apart from its impact on mortality, air pollution can also have negative effects on learning and productivity. For example, a joint study by the National University of Singapore and the Building Construction Authority concluded that the occupants of cleaner buildings were healthier and more productive<sup>3</sup>. Exposure to indoor air pollutants can lead to both acute and chronic health effects, including building-related illnesses such as sick building syndrome as well as respiratory and heart diseases.

In the US, another joint study by Harvard T.H. Chan School of Public Health, SUNY Upstate Medical School and Syracuse University also concluded that cognitive function scores were significantly better under green building conditions<sup>4</sup>.



**Figure 1** Reducing carbon dioxide levels is associated with improved cognitive function. Source: Joseph G. Allen, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino and John D. Spengler (2016). Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environmental Health Perspectives* 124 (6). <https://doi.org/10.1289/ehp.1510037>

<sup>1</sup> United States Environmental Protection Agency (1987). The total exposure assessment methodology (TEAM) study: Summary and analysis. EPA/600/6-87/002a.

<sup>2</sup> One third of global air pollution deaths in Asia Pacific. (2018) World Health Organisation. Retrieved on August 2020 from <https://www.who.int/westernpacific/news/detail/02-05-2018-one-third-of-global-air-pollution-deaths-in-asia-pacific>

<sup>3</sup> Jang-Young Lee, Pawel Wargocki, Yiong-Huak Chan, Liu Chen and Kwok-Wai Tham (2018). Indoor environmental quality, occupant satisfaction, and acute building-related health symptoms in Green Mark-certified compared with non-certified office buildings. *Indoor Air*. <https://doi.org/10.1111/ina.12515>

<sup>4</sup> Joseph G. Allen, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino and John D. Spengler (2016). Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environmental Health Perspectives* 124 (6). <https://doi.org/10.1289/ehp.1510037>

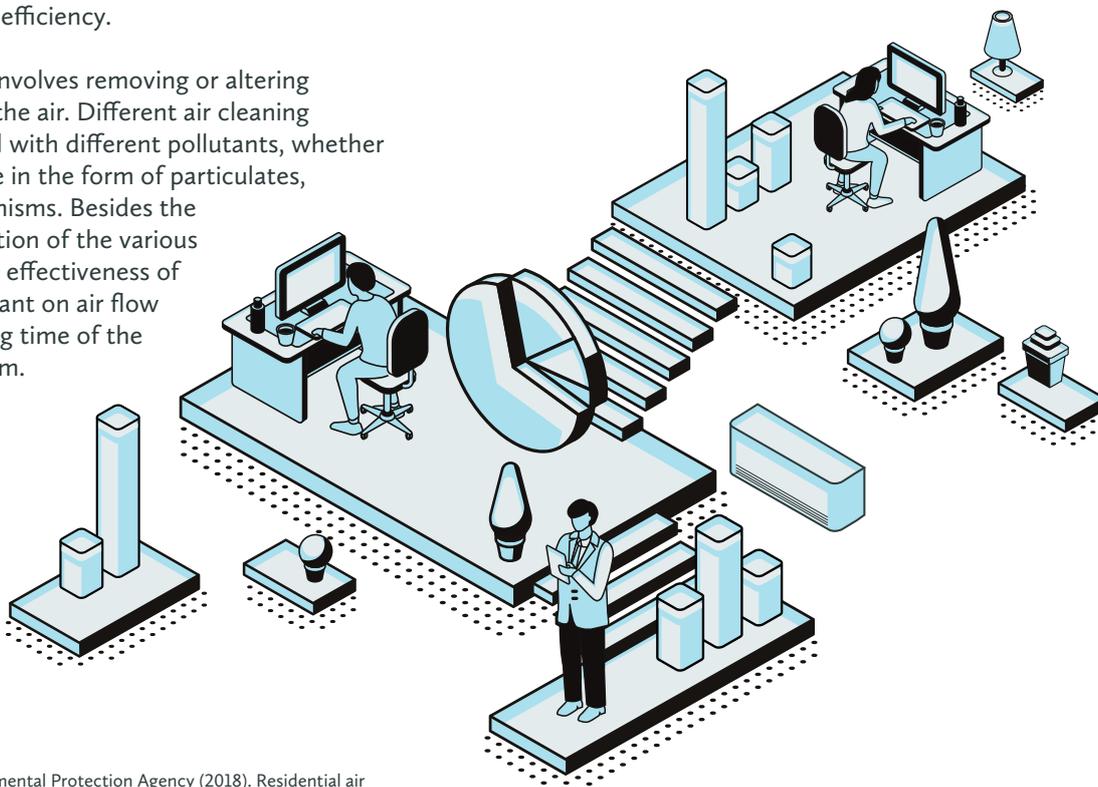
## Strategies for maintaining indoor air quality

With the COVID-19 pandemic resulting in people staying indoors for longer hours than ever, the demand for clean air indoors will only continue to rise. So how do you keep the air clean? For now, three fundamental strategies are adopted in the field of IAQ maintenance: source control, ventilation, and air cleaning.

Getting to the source of the pollutants is a good way to deal with indoor air pollution. Source control aims to eliminate sources of pollution or reduce their emissions. This is particularly relevant when dealing with the VOCs that arise from indoor furnishings such as flooring, adhesives and paints. Awareness of these pollutant sources has resulted in manufacturers designing green building materials that emit minimal VOCs. Combined with proper ventilation, source control remains the most economical and effective way to reduce indoor air pollution.

Another way is to reduce the concentration of indoor air pollutants by keeping the air moving and bringing air from outdoors in. In addition to air quality, ventilation is also crucial for regulating temperature and humidity within buildings. While building design can optimise natural ventilation, integrating more advanced ventilation controls with existing building management systems has allowed mechanical ventilation with improved energy efficiency.

Cleaning the air involves removing or altering contaminants in the air. Different air cleaning technologies deal with different pollutants, whether the pollutants are in the form of particulates, gas or microorganisms. Besides the mechanism of action of the various technologies, the effectiveness of air cleaning is reliant on air flow rate and operating time of the air cleaning system.



## The complexity of maintaining good IAQ

Despite numerous strategies to improve it, indoor air quality control is not without its challenges. The main challenge is that indoor air pollution is a complex issue: the variety of pollutants from multiple sources all require different strategies to remove them and these strategies can conflict with each other. Certain sources of pollutants are hard to remove completely, such as occupant-related pollutants and outdoor air pollution.

For effective air purification, a combination of different air cleaning technologies is required. Some technologies may also generate polluting by-products themselves<sup>5</sup>. There is also the issue of the energy efficiency. Ventilation is an important element in removing indoor air pollutants but achieving effective ventilation is not trivial, so new IAQ technologies should ideally balance optimal ventilation with energy efficiency.

To ensure good indoor air quality, there is a need for additional air cleaning measures or dynamic systems. There is room for the industry to develop solutions to address these challenges, such as more energy-efficient and cost-effective air cleaning technologies, safer solutions that minimise the production of by-products, as well as more effective solutions that can target multiple pollutants simultaneously.

<sup>5</sup> United States Environmental Protection Agency (2018). Residential air cleaners: A technical summary. EPA 402-F-09-002.



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# UNDERSTANDING THE IAQ MARKET

The global IAQ solutions market is a rapidly growing one, expanding at a compound annual growth rate of over 6% from 2020 to 2024, with a forecasted growth of USD\$9.5 billion during the same period<sup>6</sup>. Asia Pacific is predicted to be the fastest growing market, due to the increasing demand for improved indoor air quality and products in China and South East Asia.

A significant driver in this market is declining indoor air quality and an increasing awareness of the health impacts of good IAQ. The increasing demand for green buildings and the current COVID-19 pandemic are also major contributors. While studies on biological pollutants have been conducted much earlier, the COVID-19 pandemic is a key driver of the growing awareness of biological pollutants and their impact on health and safety. This report focuses on the opportunities for IAQ maintenance in the residential



and commercial segments, which deals mainly with the removal of particulate matter, gaseous and biological pollutants to create comfortable and healthy indoor environments.

## The desire for good indoor air quality

Studies have shown that outdoor air quality has declined as industrial activities and urbanisation ramp up. Living in an urban environment is almost a guarantee that you will be exposed to air pollution: studies of urban dwellers have shown that 80% of the people observed are exposed to unhealthy air quality levels that exceed the WHO guideline limits<sup>7</sup>. And it is not just about what goes on outdoors. Around the world, outdoor air pollution affects indoor air quality. However, modern life—exacerbated by the COVID-19 pandemic—requires long hours spent indoors.

More people are beginning to realise that indoor air quality has a significant impact on health. Most notably, nitrogen dioxide is strongly related to asthmatic symptoms and the risk of future asthma attacks. A study of commercial buildings in London showed that indoor air quality was consistently poor and even worse than the air quality outdoors<sup>8</sup>. Poor air quality indoors has led to the building-associated illnesses such as sick building syndrome and building-related illness, a host of acute and chronic health effects that result from exposure to poor quality air. These illnesses impact both physical health and work performance. Furthermore, the COVID-19 pandemic has helped put IAQ into the spotlight, especially given the potentially harmful effects of biological pollutants. This is largely a positive development, as it raises the importance of IAQ in the minds of decision-makers.

## The drive for green, healthy buildings

As a result of sustainability regulations, there is an increasing demand for green buildings, with one of the key goals being improving the health and well-being of building occupants through providing a good indoor environment. By definition, green buildings are designed to maximise resource efficiency while minimising adverse effects on human health and the environment.

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<sup>6</sup> Indoor air quality solutions market by product and geography — Forecast and analysis 2020-2024. (2020) *technavio*. Retrieved on August 2020 from <https://www.technavio.com/report/indoor-air-quality-solutions-market-industry-analysis>

<sup>7</sup> Air Pollution. World Health Organisation. Retrieved on August 2020 from <https://www.who.int/health-topics/air-pollution>

<sup>8</sup> How pollution affects indoor air quality in buildings. (2018) *CIBSE Journal*. Retrieved on August 2020 from <https://www.cibsejournal.com/technical/learning-the-limits-how-outdoor-pollution-affects-indoor-air-quality-in-buildings/>

In Singapore, environmental sustainability regulations are an important driver behind the rise of green buildings. So far, more than 40% of Singapore's buildings gross floor area is green. However, the country aims to have 80% of its buildings green-certified within the next ten years. In other parts of the world, governments and organisations are embarking on a similar track. For example, China's 13<sup>th</sup> Five-Year Plan for Building Energy Efficiency and Green Building Development includes a requirement for 50% of all new urban buildings to be certified green<sup>9</sup>. In China, the demand for green buildings is high enough that good IAQ at the workplace is a consideration among job seekers and employees.

As energy efficiency and operational cost savings are key components in considering if a building is green, IAQ solutions must also be energy-efficient and cost-effective. The key is to design measures that maintain good IAQ at the early stages of development. The COVID-19 pandemic has also highlighted the urgency of addressing the need for healthy buildings.

## Air cleaning value chain

There are opportunities for both local and international players all along the air cleaning value chain, which starts with the production side of technology, including producers for raw materials, components, system manufacturers and system integrators.

End users include property developers and owners, educational institutions as well as medical institutions that require pristine indoor air. Other than maintaining IAQ systems after installation, it is also important to continually monitor the level of pollutants. On the regulation side, there are certification and standard bodies, as well as government authorities. There are also various trade associations and chambers connecting the various players.

Beyond that, solution providers can find additional opportunities to apply IAQ technology in other market segments beyond human health in the residential, commercial, industrial, and transport sectors. Air quality is also a key consideration in other industries such as refrigeration, cold chain and food logistics, greenhouses and indoor farms, and environment odour removal.

<sup>9</sup> Alex Molinaroli (2017) China's clean, green buildings of the future. *World Economic Forum*. Retrieved on August 2020 from <https://www.weforum.org/agenda/2017/06/china-clean-green-buildings-future/>





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## STATE-OF-THE-ART & EMERGING TECHNOLOGIES

Current air cleaning technologies revolve around filtration, electrostatic precipitation, catalytic oxidation and UV germicidal irradiation. Opportunities for innovation and further development include increasing the energy efficiency of IAQ systems that comply with Green Building requirements, making IAQ solutions that are cheaper, safer, more sustainable and comprehensive to account for different types of pollutants.

For air cleaning solutions to become simpler and more sustainable, they must be multi-functional and able to target multiple pollutants at a time. This paper will focus on three air cleaning technologies that show promise in this area: **filtration, catalytic oxidation and biological air cleaning**. These technologies are all effective on more than just one type of air pollutant at a time, making them good candidates for addressing the IAQ problems raised earlier.

### Filtration

There are many kinds of filters, each capable of treating a different range of pollutants. Mechanical filters use media with a fibrous structure that can physically catch and remove pollutant particles from airstreams. Depending on the filter class, such filters can capture and remove particles of different sizes. Gaseous pollutants on the other hand can be removed by physical adsorption or chemisorption.

Although the filters themselves may not be expensive, they require regular maintenance and the disposal of the pollutants they catch to avoid becoming a source of pollutants themselves. This, combined with the need for filters to be replaced, adds to the operational cost. Furthermore, usage of filters results in airflow pressure drop, affecting energy efficiency. The energy cost to operate a filter makes up 80% of the total cost.

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## Catalytic oxidation

Catalytic oxidation processes activated by light are well suited to degrade adsorbed VOCs, bioaerosols and microorganisms. There is also interest in the development of new catalysts that will require less or no dependency on a light source, simplifying and boosting the efficiency of the entire system.

On the other hand, catalysts are expensive on their own, and the additional UV light source incurs extra costs. As most buildings do not come with this technology, there are also installation and adaptation costs to consider.

## Biological methods

Biological methods of cleaning air include purification materials and systems based on plants, plant extracts, bacteria and enzymes. These biological methods are mainly used in industrial water and air treatments. While not a mainstream method of indoor air cleaning, certain plant-based biofiltration solutions such as 'green walls' are becoming an increasingly popular way to improve IAQ<sup>10</sup>. While they represent a sustainable solution, the effectiveness and capacity of these biological methods still require further studies.

### Types of Pollutants Removed by Different Air Cleaning Technologies

Technologies	Pollutants							
	Particulate matter	Gaseous						Biological
		Carbon dioxide	Oxides of nitrogen (NOx)	Volatile organic compounds e.g. formaldehyde	Odours and fragrances	Ozone	Moisture	Microbes/ Allergens
Fibrous filter media	✓							✓
Adsorbent media		✓	✓	✓	✓		✓	
Chemisorbent media		✓	✓	✓	✓			
Catalytic oxidation		✓	✓	✓	✓	✓		✓
Biological		✓	✓	✓	✓			✓
Ozone		✓	✓	✓	✓			✓
Plasma		✓	✓	✓	✓			
Ionisers	✓							
Electrostatic precipitation	✓							
Ultraviolet germicidal irradiation (UVGI)								✓
Thermodynamic sterilisation								✓

Figure 3 The multi-functional capabilities of advancing air cleaning technologies.

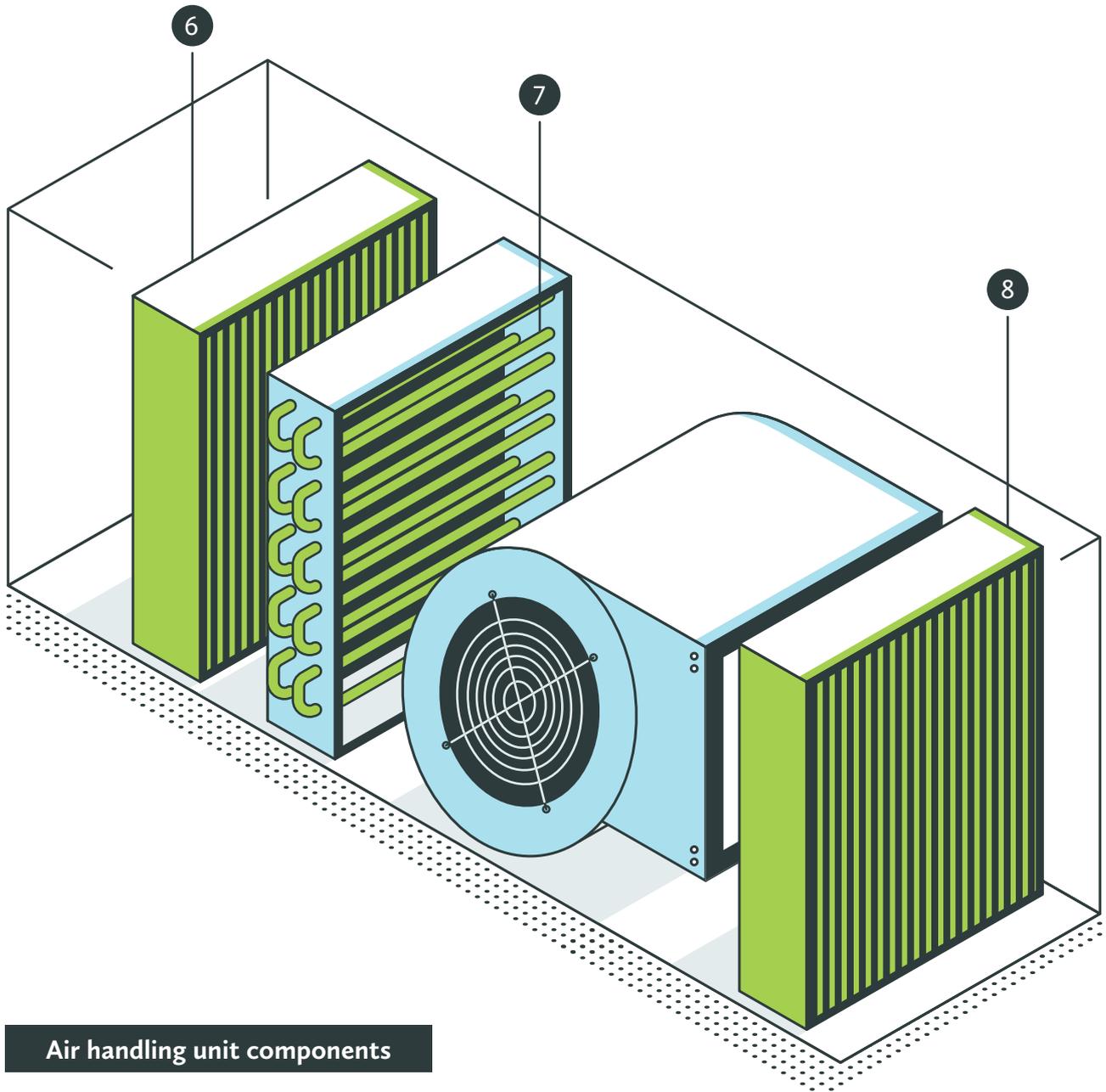
<sup>10</sup> Courtney McKay (2017). Green walls: A growing trend. *BOMA Magazine*. <https://fmlink.com/articles/green-walls-growing-trend/>

# TECHNOLOGIES ON THE HORIZON



Typical office setting

- 1 Window**
  - Self-assembled nanofibrous filter
- 2 Wall-mounted panels**
  - Indoor carbon capture using microfluidic photosynthetic algae system
- 3 Air conditioner**
  - Coating with odourless microorganisms to improve indoor air quality
  - Filtration medium with electrospun metal oxide nanofibre layer
- 4 Air purifier**
  - Microalgae air purifier
  - Self-catalysed antimicrobial coating
- 5 Surfaces**
  - Stable, plant-based photoactive antimicrobial agent
  - Antimicrobial transparent coating for surfaces and surrounding air

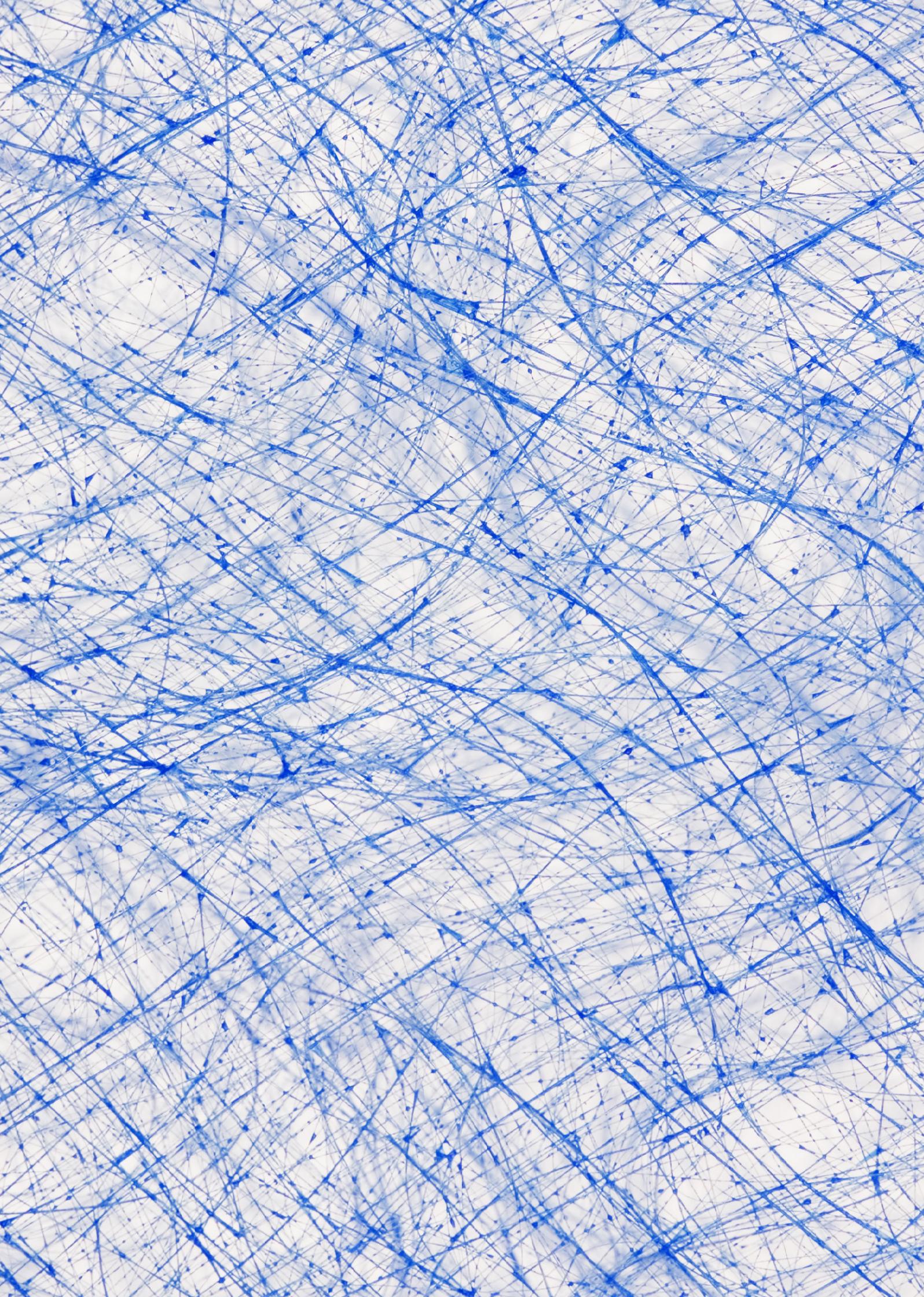


## Air handling unit components

- 6 Filter 1**
  - Acoustic aided air filter
  - Self-catalysed antimicrobial coating
- 7 Cooling coil**
  - Coating with odourless microorganisms to improve indoor air quality

- 8 Filter 2**
  - Nano-metallic catalyst filter
  - Self-assembled nanofibrous filter
  - Macrocyclic compound for removal of odours and VOCs

*Diagrammatic representations for example and illustration purposes, not drawn to scale.*



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## AIR CLEANING MATERIALS PATENT LANDSCAPE

The patent landscape provides insights into the innovation activities surrounding the development of air cleaning materials technologies. In recent years, there has been an increasing trend in patent applications and publications relevant to IAQ. Surveying the worldwide patent database for relevant patents filed between January 2013 and December 2019, we identified a total of 750 patent families.

### Where: China and US are the top countries for patent applications

China holds the largest number of patent applications, focusing mainly on the growing trends of catalytic oxidation and biological air cleaning methods. US organisations, coming in second, dominate patent applications in the more mature market of filtration technology. Patents from Europe and other Asian organisations, mainly in Germany, Japan and Korea, focus on catalytic oxidation and filtration technologies.

### Who: System developers and material design

Key inventions in this patent landscape relate to the development and design of air cleaning systems and their components. The majority of patent applications are within the air cleaning system development domain, which is dominated by catalytic oxidation systems that target the removal of VOCs. The rest of the patent applications are in the development of new filter materials and designs, as well as materials for biological and catalytic oxidation systems. These include catalysts and other elements such as coatings and sprays.

### What: Filtration leads the pack

Patent citations, a measure of how many times a given patent is referenced by other patent applications, are a proxy for how impactful an invention is on subsequent inventions. Of the three technologies, filtration technology leads the citation list, with the most cited patent on multi-layered nanofibre filter with electrospinning getting 68 citations. Next on the list is a development in catalytic oxidation, cited 28 times, describing a  $\text{TiO}_2$  catalyst that uses a plasma reactor to disinfect and purify air without additional UV light. Air cleaning with biological methods is relatively understudied, with the top publication for a low-cost purifying spray made from plant extracts cited 8 times.

## Trends in IAQ research and development

In general, the application and publication trends of the highlighted air cleaning technologies have grown in recent years. This reveals the increasing scope of technological innovation to cope with rising demands for good IAQ.

Being a mature and stable market, new patent applications for filtration technology occur at a relatively steady rate. The current research in this area trends towards improving performance, functionality and energy efficiency. However, there is still room to develop solutions to deal with the other shortcomings, such as the need for frequent maintenance and replacement.

Catalytic oxidation is gaining traction as a strategy for indoor air purification, a trend reflected in the growing technology development within the field. Advancing technological developments related to this method are shifting away from photocatalysis, which may translate to more energy-efficient and less costly systems.

Though still emerging, biological methods focus mainly on the removal of VOCs and tackling biological contaminants. The non-toxicity and environmental friendliness of this method are its key motivators.

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**FOR AIR CLEANING SOLUTIONS TO BECOME SIMPLER AND MORE SUSTAINABLE, THEY MUST BE MULTI-FUNCTIONAL AND ABLE TO TARGET MULTIPLE POLLUTANTS AT A TIME.**



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## CONCLUSION

Though invisible and often ignored, IAQ can have a profound impact on human health. At this current juncture, no single air cleaning technology can perform a job as well as a combination of at least two air cleaning technologies. Such combined use is likely to be unavoidable in the near future, but there is a potential of minimising the combinations needed with multi-functional technologies. Advances in improving current air cleaning technology, including the search for multi-functional materials that can deal with the complex requirements of IAQ maintenance in a sustainable, energy efficient manner, will shape research and product development efforts in the field.

As this paper shows, the IAQ research field is rapidly growing to meet rising consumer and regulatory demand. The overview of current research trends and advancing technology, as well as the richness of the patent landscape shows that this is a field where further research and technological innovations are welcome.

Accompanying this white paper is a detailed market trend and technology landscape study report. If you would like more details and to learn about the opportunities outlined in this report, please contact: [techscout@ipi-singapore.org](mailto:techscout@ipi-singapore.org).

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