Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Sustainable solutions for indoor pollution abatement during COVID phase:  
A critical study on current technologies & challenges

Shilpa Patial a, Mohammed Nazim b,*, Aftab Aslam Parwaz Khan c,*, Pankaj Raizada a,*, Pardeep Singh a, Chaudhry Mustansar Hussain d, Abdullah M Asiri c

a School of Advanced Chemical Sciences, Faculty of Basic Sciences, Shoolini University, Solan (HP) 173229, India  
b Department of Chemical Engineering, Kumoh National Institute of Technology, 61 Daehak-ro, Gumi-si, Gyeongbuk-do 39177, Republic of Korea  
c Center of Excellence for Advanced Materials Research, King Abdulaziz University, Jeddah 21589, Saudi Arabia  
d Department of Chemistry and Environmental Science, New Jersey Institute of Technology, Newark, NJ 07102, United States of America

A R T I C L E   I N F O
Keywords: Indoor pollution Covid-19 pandemic Indoor air quality (IAQ) Engineering technologies Sustainable solutions

A B S T R A C T
The appearance of the contagious virus COVID-19, several revelations and environmental health experts punctually predicted the possibly disastrous public health complications of coexisting catching and airborne contamination-arbitrated disease. But much attention has been given on the outdoor-mediated interactions. Almost 3.8 million premature deaths occur every year globally due to the illness from indoor air pollution. Considering the human staying longer span indoors due to restricted human activities or work from home, the indoor air quality (IAQ) might show prominent role for individual health life. Currently, the Environmental Protection Agency (EPA) ensures no regulation of indoor airborne pollution. Herein, the paper underlines the common bases of indoor air pollution, poor IAQ, and impacts of the aerosolized airborne particles on the human health. In order to address these challenges and collective contagion events in indoor environment, several emerging control techniques and preventive sustainable solutions are suggested. By this, more innovations need to be investigated in future to measure the impact of indoor air pollution on individual health.

Introduction: living with covid phase

Sources of coronavirus

At the end of 2019, the corona virus originated in China's Huanan seafood market and spread to various countries worldwide resulting in a corona pandemic as the COVID-19 virus outbreak (Wang et al., 2020). The covid variant, SARS-CoV-2 was initially found in three patients of Jinyin Hospital, Wuhan on December 30, 2019 (N. Zhu et al., 2020). All viruses are composed of pleomorphic RNA infections with peak size of <150 nm and <32 kb positive extremity (Zaki et al., 2012). In addition, coronaviruses were found firstly in the 1960s in patients' noses which is a reason for different viruses as common colds (Kahn and McIntosh, 2005). However, infected patients have common symptoms of pneumonia, and influenza which were inquired by lab analysis (Bhatia et al., 2020; Patial et al., 2022). The scientific classification of coronavirus:

Family: Coronaviridae  
Subfamily: Orthocoronavirinae  
Order: Nidovirales

Suborder: Coronidovirinae  
Genus: Betacoronavirus  
Subgenus: Sarbecovirus  
Species: Severe Acute Respiratory Syndrome Corona Virus-2 (SARS-CoV-2).

The extreme COVID cases were propagated through breathing disorder via a respiratory system in pneumonic cells of pneumocytes in a hyaline membrane (Xu et al., 2020). In addition, SARS-CoV-2, beta coronavirus variant contains a solitary strand of Ribonucleic Acid (RNA), thirty-two kilobases in length which is an active point of RNA infection genome (Lu et al., 2020). Thus, coronaviruses have elevated recombination of positive-strand RNA infection, and indiscriminately hereditary data of virus-infected hosts to reduce immunization and treatment against virus species. In general, coronaviruses cause respiratory illness due to SARS-CoV-2 and MERS coronavirus (MERS-CoV) variants with pathophysiological development of SARS-CoV-2, which support further reaction of pneumonia (Fehr and Perlman, 2015). Among these coronavirus, SARS-CoV-2 has shown the most dangerous and uncontrollable symptoms in humans for a large number of cases with no specified drugs for cure and protection till now.

https://doi.org/10.1016/j.hazadv.2022.100097
Received 17 April 2022; Received in revised form 17 May 2022; Accepted 22 May 2022
2772-4166/© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
S. Patial, M. Nazim, A.A.P. Khan et al.  
Journal of Hazardous Materials Advances 7 (2022) 100097

Fig. 1. Origin and transmission of coronavirus. Reprinted with permission from Ref (Guo et al., 2020).

In addition, SARS-CoV-2 has four structural proteins with the spike protein (S), an envelope protein (E), membrane protein (M), and nucleocapsid (N) protein (N) with ∼30 kb genome (Zhou et al., 2020; D. Kim et al., 2020). In the SARS-CoV-2 genome, various open reading frames (ORFs) are encoded for infected humans having >60% of viral-based transcriptomes to establish basic cell biology alteration after human cell infections (D. Kim et al., 2020; Jungreis et al., 2021; Stewart et al., 2018). Such viruses have explored recombination in infected hosts. Recently, the SARS-CoV-2 virus strain found in bats from Yunnan Province, China which is called “RaTG13” based on its origin from horseshoe bat, Rhinolophus-affinis species via genome sequence matching of ∼96% with SARS-CoV-2 strain which suggest compact relation between the two viral strains (Zhou et al., 2020). Principally, the SARS-CoV-2 genome contains protein-coding sequences shared with different coronavirus species and nucleotide substitutions might modify protein structure via amino acid change (Yi, 2003). During non-synonymous substitutions, amino acids might change the functional properties of resulting proteins to provide a natural selection process. In comparison, synonymous substitutions are less “visible” to natural selection because of their poor effect on produced proteins (Akashi, 1994; Chamary et al., 2006; Nei, 1987). Owing to natural selection, nonsynonymous substitutions occur rarely to protect proteins from major modifications in amino acid sequences in genomic viruses. Thus the average ratio of nonsynonymous to synonymous substitutions is ∼0.226 but it was only ∼0.028 for the SARS-CoV-2 genome after being studied with 9 ORFs of virus (X. Tang et al., 2020). Hence, it was postulated that
ORFs were preserved after danger mutations exclusion in the SARS-CoV-2 virus. Hence, the ratio has been observed to be lower than other mutants of coronaviruses 20 resulting in the high strength of selection of the SARS-CoV-2 genome. As synonymous substitutions are controlled by mutation genome rates provide high stability compared to specific amino acid sequences selection. The average similarity between RaTG13 and SARS-CoV-2 is estimated at 83% (not ~96%) if synonymous substitutions only provide longer relation. We can utilize this metric to estimate the time of divergence between SARS-CoV-2 and RaTG13 (X. Tang et al., 2020; Boni et al., 2020). In addition, synonymous substitutions estimated rates found from 1.67 to 4.67 × 10⁻³/site/year as reported earlier. Li et al. (Li et al., 2020) and Chaw et al. (Chaw et al., 2020) demonstrated mutation rates of 1.9–3.1 × 10⁻³/site/year and 1.5–3.3 × 10⁻³/site/year, respectively in the SARS-CoV-2 virus resulting in divergence time of ~18 and ~71.4 years for SARS-CoV-2 and RaTG13, respectively. The generation times of viruses are extremely short (in tissue cultures, SARS-CoV-2 could generate 103 virions in 10 h), and SARS-CoV-2 and RaTG13 are, rather divergent (Dabravolski and Kavalionak, 2020). The huge diversity of coronaviruses in bats like mammals should give a well-matched virus strain as SARS-CoV-2. Due to the close similarity of RaTG13 to SARS-CoV-2, the substantial sequence variation takes from 93.1 to 99.6% range in mutation rates (Li et al., 2020). Based on phylogenetic comparisons and detected recombination, coronavirus strains of SARS-CoV-2 exhibit long and complicated recombination to produce different genomic segments and genetic divergence with virus strains other than RaTG13. The genome of SARS-CoV-2 might be combined ‘recombination blocks’ as Boni et al. reported large recombination breakpoints with the highest frequency in ORF1a with the region marking the N-terminus of the S protein (Boni et al., 2020). Recently, the coronavirus-based pandemic has been diagnosed via vaccines using nanomaterials for the treatment of fly-like features resulting from lung and abdominal problems (Rangayasami et al., 2021). Some years ago, the MERS virus show pathogenic contamination and transferred from bats to humans in Middle East countries (Cui et al., 2019; Pirouz et al., 2020; Organization, 2020). The environmental conditions have a direct impact on virus spread with significant factors such as dust, heat, air quality, temperature, and wind speed resulting in the stickiness of day and night (Shaffiee Haghshenas et al., 2020). Due to topographical similarity with China, Vietnam faces a huge danger of virus transmission (CSSE). According to World Health Organization, covid-19 has been considered a ‘General Health Emergency of International Concern’ in January and ‘Pandemic’ in March 2020 (W.H. Organization 2020). Until now, over 303,977,077 infected people and 5464,185 people have been died worldwide by coronavirus resulting in lockdown in most of the countries which severely damage economic growth. From a social point of view, distancing and masking has been proving effective measures along with other precautions such as the gathering of people to protect from the corona pandemic spread (Rangayasami et al., 2021).

The covid virus has been spread through water, breathing droplets such as sneezing or coughing, and aerosol materials from virus-infected persons. The virus infection has widely spread through contact and unmasking in public places with hatching from ~14 days after virus infection. Recently, the Covid-19 pandemic is severely spread by respiratory tract infections with different variants of SARS-CoV via oral, and facial ways, and SARS-CoV-2 might be transferred from vaporizer or mother to infant (Dong et al., 2020). Thus, the human transmission happens in an intimate contact through the respiratory droplets <10 μm in diameter or coughs via respiratory pathogens. As these droplets might stuck in mucosa and lungs after air-breathing and can be contaminated by COVID-19 by getting into contact with polluted surfaces followed by touching their nose, mouth, or eyes (Emergencies and Preparedness, 2020; Purohit et al., 2020). Furthermore, nanoparticles might support such pathogens before they break into the human body with various objects and surfaces and are hugely distributed on various objects to enter through nanoparticles and attack the virus infections (Nano, 2020).

**Type of coronavirus**

Coronaviruses are made up of positive-strand RNA which is found in animal species to originate disease symptoms in various hosts (Wertheim et al., 2013; Woo et al., 2012; Jonassen et al., 2005). On the basis of genetic and serological features, coronaviruses are majorly classified into four types

1. Alpha-coronavirus (α-CoV),
2. Beta-coronavirus (β-CoV),
3. Gamma-coronavirus (γ-CoV), and
4. Delta-coronavirus (δ-CoV)

These viruses diverge in ~2400–3000 BC4 range to infect various host animals. However, α and β-CoVs (Fig. 2a) found in diverse mammals, while γ and δ-CoVs originate majorly from birds, and fishes along with cetaceans infections as beluga whales and bottlenose dolphins of γ-virus (Jonassen et al., 2005; Ma et al., 2015; King et al., 2018). Various types of SARS, MERS, and COVID-19 virus originate epidemic and pandemic outbreaks in human beings which belong to a subgroup of β-type coronavirus known as Sarbecovirus (Lefkowitz et al., 2018), which are majorly abundant in bats and its mammal family. All four coronavirus strains display weak symptoms of common cold (Fig. 2b) where HCoV-229E, and HCoV-NL63 have α-coronavirus family, while HCoV-OC43 and HCoV-HKU1 belong to β-coronavirus as Embecovirus (Lu et al., 2020; Lai and Cavanagh, 1997).

The virus present in host animals exhibits relative recombination among virus strains resulting in the diversification of coronaviruses including SARS-CoV-2, β virus, and Omicron as potential virus strains for spreading and infecting human cells.

**Infections to human beings**

By internalization of a virus into a host cell might reproduce it efficiently. The SARS-CoV-2 virus enters body cells from endocytosis using better effective cathepsin L than cathepsin B (Forni et al., 2017). The human ACE2 is a major receptor for SARS-CoV-2 virus along with lysosomal cathepsins for endocytosis as reported for SARS-CoV and MERS-CoV (Jungreis et al., 2021). The infected RNA behaves like mRNA which is translated and replicated by ribosomes for viral enzymes to convert into new viral genomes (Stewart et al., 2018). In addition, RdRp is the major component of the viral transcription and replication system as an active target for antiviral drugs for corona vaccine development (Viehweger et al., 2019). The coronavirus explores the protein translation process using the host materials and splits proteins viral main protease (Mpro)- and papain-like protease (PLpro) systems (Zhao et al., 2004). The respiratory syndrome coronavirus, MERS-CoV, and SARS-CoV viruses speed infected due to a high rate of transmission with functionalization of a receptor-binding section of S-protein up to ~14 days incubation time (Kanmodi and Kanmodi, 2020; Y. Zha et al., 2020; Khan et al., 2020). The transmission of the virus majorly occurred by contact, inhalation, or respiratory droplets from an infected person to cause respiratory illness, or distress, pneumonia-like, or cytokine syndrome (Fig. 3) (Zhang et al., 2020). During the corona pandemic, various rules, restrictions, and policies by different countries such as restricted mobility, travel bans, testing and screening of travelers, and closure of organizations and schools is to decrease the contact and infectious risk of susceptible persons from infected one. At the early stage of the COVID-19 pandemic, it becomes a challenge for public health decision and strategy makers to combat with the virus due to the lack of sufficient knowledge about the nature of the virus and its transmission mechanism. Airborne transmission could be widely accepted as one of the prominent pathways among all transmission routes introduced.
Fig. 2. (a). Schematic depiction of the four genera of coronaviruses, their evolutionary relationship, and their animal hosts, (b) Genomic distribution of all open reading frames (ORFs) across the 29,903 bp SARS-CoV-2 genome. The nucleocapsid (N), spike (S), membrane (M), and envelope (E) proteins are color-coded according to the image of the virus. All other ORFs correspond to nonstructural proteins. The yellow panel shows an enhanced view of an 8340 bp region encompassing 9 ORFs and the three-prime untranslated region (3'-UTR). Reprinted with permission from Ref (Singh and Yi, 2021).
Household pollution (either indoor or outdoor conditions) are considered a critical parameter for virus viability and enhanced the infectious risk of COVID-19 exposure.

Recent studies suggested that the mortality rate also depends on the level of indoor pollution. Based on the world health organization (WHO) data, the mortality rate is more pronounced for people suffering from high blood pressure, cardiovascular disease, diabetes, and severe respiratory disease (Singh and Mishra, 2021). The socio-demographic parameters such as lack of basic amenities, or bunched slum dwellers, density around public transport, traveling period, the infrastructure growth as well show an increasing impact on the COVID-19 cases (Das et al., 2021).

However, there is still an unusual debate between scientists and researchers about the contagious pathway of spreading viruses from person to person through airborne communication, particularly in indoor spaces. In addition, numerous studies described diverse results that create more debate (Liu et al., 2020; Santarpia et al., 2020; Stadnytskyi et al., 2020; Chia et al., 2020; Orenes-Piñero et al., 2021). The aerosolized particulate matter (PM) (particles < 2.5 aerodynamic diameters) is primarily measured as the most environmental health threat factor causing millions of deaths per year worldwide (Zhao et al., 2018; Kumar et al., 2022). Therefore, this paper aims to address the various preventive sustainable solutions to curb the airborne transmission of COVID-19 viruses and emerging control strategies to preserve IAQ. Moreover, focuses on variant factors affecting IAQ and resident’s health that proved better solution and pave in a more appropriate way for a sustainable solution.

**Indoor pollution issues during “Living with covid phase”**

**Aerosols**

Aerosols particles play the most exciting and significant role to spread SARS-CoV-2 virus in different living beings. The SARS-CoV-2 virus might be viable in aerosols for long time up to hours or days resulting in huge and fast virus distribution over huge distances. Aerosols might create super-spreader events for the virus in this pandemic time. During COVID-19 outbreak, fewer contaminants were noticed in most parts of the world in ambient air because of a wide-range of social restrictions, activities, work, and travel movements (Nadzir et al., 2020; Marczazan et al., 2001).

As most of the people spent much time inside their homes due to various restrictions, which relocates human exposure to various pollutants. Moreover, such poor air quality significantly increased the mortality rate of respiratory disease patients in the socio-demography (Zwoździak et al., 2015). The industrialization, livestock farming, and combustion of fossil fuel from power plants and vehicles are some of the critical anthropogenic activities responsible for the deterioration of air quality. These activities persuade the emission of PM, O₃, SO₂, CO, and NOₓ gasses which turns harmful when exceeding acceptable limits and may accelerate the viral infection.

**Particulate matters (PMs)**

The PM₂.₅ is a solid aerosol with a diameter of ≤ 2.5 μm particles suspended in ambient air. It has been reported that long-time exposure to PM₂.₅ is significantly detrimental to the human body by inhaling such fine PMs moves into the human lungs (Wang et al., 2006; Gemenetzis et al., 2006; Qian et al., 2008). In addition, PM₂.₅ has a long life in the air and is swiftly suspended in comparison to liquid droplets (Fig. 4a, 4b) which is a significant threat to a doctor's health for a long time indoor conditions (Ren et al., 2021). The PM₂.₅ can be stacked on walls, the floor of hospitals chairs, table equipment’s surface materials and quite easily moved by thin turbulence in the air from normal physical activities such as people moving, and walking (Liu et al., 2018; Chatoutsidou et al., 2015; Hanninen et al., 2005; Zhang and Cao, 2015; National Ambient 2022). The viability of SARS-CoV-2 has been reported on different types of surfaces like plastic for 72 h, metals for 48 h, cardboard for 24 h, and copper for 4 h which make them a potential matter for PM₂.₅ for redistributed/transported in the air (Van Doremalen et al., 2020; J.-M. Kim et al., 2020).

Recent reports showed that SARS-CoV-2 is carried by PM₂.₅ after healthcare peoples remove their PPE clothes from the air atmosphere. In continuation, the suspended tiny particles might add to living organisms (< 5 μm diameter) during aerosolization in a dusty air atmosphere. However, the size of the SARS-CoV-2 is in the 70–90 nm range, which might produce a new model of the virus spread (Amoatey et al., 2020). In addition, the pollutants are formed indoors as a result of cooking/frying, paints, cleaning/dusting activities, and some religious pursuits such as burning candles or incense, and workstations that may affect people’s health residing indoors (Ren et al., 2021; Chang et al., 2021). In a study by Ren et al. the implication of physical barrier in a workstation enclosed spaces to limit the airborne aerosol spread through modified ventilation and changed air supply rate (Santomaro et al., 2021). By considering ~70 cm barrier height, a distance of 4 m from the outlet along with sufficient ventilation has decreased the infectious risk by ~72%. Thus, the present study offers a cost-effective mitigation technique for limiting the transmission probability.
**Polycyclic aromatic hydrocarbons (PAHs)**

Owing to their structure, PAHs majorly belong to organic solid materials with colorless, white, or pale-yellow colors and consist of many chemical compounds with variable toxicity. PAHs have adverse effects on living organisms and insert into the air environment via different surfaces. Indoor pollution in rural areas related to solid fuels is severe due to incomplete combustion of solid fuels, which is a contagious rising concern. Acute domestic indoor pollution has induced adverse health outcomes, and about 2.31 million premature deaths were caused by household indoor pollution worldwide, deemed for approximately ~34.6% of the PM-related premature fatality rate (Coccia, 2021). A study in China indicated that ~43% of the premature death rate is related to PM2.5 (~2.5 mm size of aerodynamics) exposure contributed by the usage of residential solid fuels, causing more than ~0.52 million mortality rate per year (Zhao et al., 2018). Earlier studies have suggested the extra transmittable risk of COVID-19 infection in indoor environments, including hospitals, offices, and classrooms (Domingo and Rovira, 2020; Espejo et al., 2020). In-hospital environment during the epidemic, the confirmed patients of COVID-19 occupying more than 50% of the rooms raised the concern of high risk of surface contamination by SARS-CoV-2 (Berna et al., 2021).

**Volatile organic compounds (VOCs)**

In corona time, COVID-19 virus cure and detection based on RT-PCR standard test on nasopharyngeal and oropharyngeal swabs as the gold standard. Even with their high selectivity, sensitivity, and specificity, RT-PCR needs many particular facilities with the time-consuming process and well-trained health workers. Such methods might be uncomfortable for many patients due to the offensive sampling method (Wintjens et al., 2021). resulting in a lack of adaption on large-scale and rapid analysis (Kurstjens et al., 2020). Therefore, a novel, efficient diagnosis technique is the need of the hour to tackle the growing number of virus-infected persons for precise screening strategies (Broza et al., 2015). In respiratory tract infection, the interaction of pathogenic viruses and the environment of the body produce various particular and distinctive VOCs (Chen et al., 2020; Haick et al., 2014). Such VOCs are released after metabolic degradation in the body as gaseous products with diverse compositions of an infection or a malignancy pathologic processes (Boots et al., 2015). These VOCs might be produced through exhalation and tested using 2 basic methods, gas-chromatography and mass-spectrometry (GC-MS) which is capable of analyzing individual compounds or using an electronic nose (eNose) with pattern-recognition of chemical compounds using multivariate analysis (Farraia et al., 2019; Ahmed et al., 2017). The presence of VOCs in the early stages of infection differ between patients with certain diseases from lung infections to cancer in different patients (Traxler et al., 2018; Broza et al., 2019; van Keulen et al., 2020; Lamote et al., 2020). Thus, the VOC-based COVID-19 screening method has a promising way to provide a fast, simple, non-invasive, point-of-care diagnostic tool and easy to apply for mass screening, and ultimately optimizes COVID-19 control strategies and might be a good competitor or replacement to RT-PCR test analysis (López-Feldman et al., 2021).

![Fig. 4](image-url) (a) Physical barrier set up in the location of the office, (b) infection risk for multiple contaminant sources (A, B, and C) with modified ventilation means. Reproduced with permission from ref. (Ren et al., 2021) with license number [5,177,491,160,146], Copyright Elsevier 2021.
Thus, various contaminants like PAHs, PMs, and VOCs in indoor environments are mainly associated with COVID-19 transmission. The relative moistness in the indoor atmosphere also influenced the COVID-19 infection by modifying the period airborne, contagious particle’s aerdynamic width, and viability (Agarwal et al., 2021).

**Engineering technologies**

The defensive measures such as social distancing, wearing masks, or lockdown could be followed only till the authorities have strictly imposed them. However, these safety measures do not offer a permanent solution to combat this virus in the future. These epidemic situations alarm technologists to investigate good control strategies that could be beneficial in thwarting bio-attacks. Air purification and sufficient ventilation could prove effective strategies in improving residential health and protecting from infectious risk of COVID-19 transmission. These important engineering control strategies are further elaborated displaying their application and usefulness (Fig. 5) (Agarwal et al., 2021).

**Increasing outside-air ventilation**

People spend more than 80% of their time in indoor rooms (Fig. 6), dilution of air pollutants inside the spaces should be the key aspect to minimizing exposure to infectious-risk and for people’s healthy environment (Z. Tang et al., 2020).

Thus, considering the sources, levels, and development of PM indoors is significant for the correct assessment of human health risks to aerosols exposure. Ventilation is considered one of the prime engineering control technologies for preserving IAQ. Normally, it is found that opening windows for ventilation or indoor-outdoor exchange can improve the IAQ value. Ventilation could also be provided mechanically via heating, ventilation, and air conditioning (HVAC) systems in addition to natural ventilation from windows, vents, louvers, etc. Sufficient ventilation is essential for decreasing the contagion risk in restricted places, including public buildings, vehicles, offices, and residential areas. However, higher ventilation doesn’t declare the complete elimination of the virus, but a greater amount of viral concentration could be reduced through dilution of contaminants. The WHO has suggested a 288 m³/h rate of ventilation per person for healthcare settings achieved only through mechanical or natural ventilation (Jeong et al., 2022). However, natural ventilation could not be possible in public buildings like offices, where mostly front buildings have an immovable glass covering, and hence, installation of the mechanical system is preferred.

**Increasing air filtration**

Employing filtration and air cleansing methods to improve the IAQ by removing the maximum amount of aerosol particles (i.e., tiny particles containing viruses). It is significant to use these methods along with sufficient ventilation and source control technologies because only air cleaning could not always be cost-effective to achieve high IAQ. Increasing filter efficacies in present HVAC systems either by the usage of the highest Minimum Efficiency Reporting Value (MERV) or raising the level of the air filter to MERV-13 or higher. In most cases, minimal modification to these systems can improve their efficiency rate through proper installation, replacement, and sizes as per the manufacturer’s instructions. Although the HVAC systems are employed for controlling the infectious rate of the virus, their improper implication can also exacerbate the indoor environment and can itself becomes the source of infection transport. Moreover, these systems usually recirculate the air which would become the source of increasing infection rate as carrying fresh air needs more energy, so the recirculation can also be a source of the increased rate of infection. On the other side, portable air cleaners are considered an alternative filtration technique. This strategy is a replacement of other conventionally used filtration or ventilation systems with infeasible measurements or for higher targeted filtration (e.g., in a doctor’s office) (Wargocki, 2015).

**Adjusting or reconfiguring air flows**

To reduce indoor airborne viral transport among people inside, reconfiguration of building layouts/ or rooms is an important parameter. This could be done by redirecting or exhausting all lavatories airflows towards the outdoor direction and adjusting airflow directions so that they do not setback directly from one individual to another if possible (Deng et al., 2017).

**Placement of dry ice**

The normal air is accompanied by ~21% oxygen, ~78% nitrogen, and ~0.04% carbon dioxide and concentration higher than ~0.5% (~5000 ppm) becomes hazardous. The outdoor-indoor exchange airflow is considered sanitary ideal to evaluate the IAQ value, and also a significant strategy to determine the gas discharge content per unit time. The usage of dry ice in indoor spaces could help maintain the CO₂ level which ultimately contributes to air pollution control. In an experiment, CO₂ was used as tracer gas (from human breathing or dry ice sublimation), to measure air exchange flow after the penetration of pollutants from the exterior to the interior of the indoor. For human breathing, the indoor air-exchange flow is determined using various derivation formulae, including analytic solution method, steady-state and difference method (box model) (CIDC, 2021).

**Cleaning and disinfection**

According to the centre for Disease Control and Prevention (CDC), in most cases, cleanliness using detergent or soap, without any disinfection is not enough to minimize the risk of infection. Disinfecting strategy (e.g., hydrogen peroxide and peracetic acid) is mainly endorsed in confined spaces or indoors where there has been found some confirmed COVID-19 cases. The chemical disinfectants include alcohol, phenols, chlorine, chlorine compounds, etc. The viral transmission risk from air or surfaces could be easily reduced through the proper wearing of personal protective equipment (PPEs), face masks, hand washing, sanitization, and practicing other precautionary measures to preserve healthy facilities (Brilli et al., 2018).

**Indoor plantation**

Plants improve IAQ through several mechanisms i.e., photosynthesis process, increase moistness due to emerging water vapor through microscopic leaf pores, absorbing contaminants present at the outer surface.
of the leaves and plant root-soil systems. But surprisingly there is incomplete knowledge about which plant species are best for absorbance of toxins and their effects on IAQ value. In 2019, the national AQI was found to be five times higher than the WHO’s suggested exposure levels. In a report, Brilli et al. discussed that indoor plantation could not replace the modern heating, HVAC systems (Fig. 5), and ventilation, but integrating them with computerized network technologies or smart sensors could be a more cost-effective and sustainable solution for indoor air cleaning (Liu et al., 2015). Very recently, Vyoh- an effective and sustainable biophilic filtration system is introduced with minimal maintenance. Future research is required to focus on identifying the important characteristics of high-performance indoor plant species, such as physiology (CO₂ assimilation rate), anatomy, and morphology (i.e., leaf size and shape).

**Emerging materials**

Recently, new biodegradable and cost-effective innovation includes biomaterials such as soybean. Soy protein isolate (SPI) is considered the best protein among all three soybean derivatives owing to its cost-effectiveness and great protein content (~90%). SPI might attract PM elements because of dipole-dipole interaction and electrostatic force of attraction. The SPI interacted bacterial cellulose (BC) prepared during gluconate-cetobacterx linus fermenting reaction with 3D nano-network channels mainly helps to filtrate PM particles with almost ~99% of removal efficacy. Recent solid oxygen purifying (SOP) filter is investigated to inactivate aerosol contaminants with the self-disinfect property. These filters are implemented in HVAC systems and face masks to restrict the airborne virus from spreading. SOP filters contain high
oxygen-producing neutralizing compounds, which converts air contaminants into oxygen generating hydrogen peroxide (H₂O₂) as secondary by-products (used to kill or inactivate virus). In 2015, Liu and the co-researcher investigated polyacrylonitrile filters constructed using nanopolymers and employed them to filter aerosolized particles (Fegert et al., 2020). These translucent filters can be fixed near the windows where it could allow natural light from outdoor with additional merits of maximum filtering efficacy (about 95%), high optical transparency, and low resistive airflow. Previously, activated carbon was the most commonly employed technique for the filtration of PM particles through the adsorption process. High-efficiency particulate air (HEPA) system was the most popularly conventional filter with ~99.97% rate of aerosol removal but was less employed due to its high cost.

The present day, UV light is in great demand owing to its ability to self-disinfection and can inactivate viruses through DNA rupturing. The photo-catalytic-oxidation (PCO) is the recent emerging filter that uses TiO₂ (oxidizing agent) and is potential enough to remove every type of contaminant but releases ozone gas as a by-product. Therefore, these above-mentioned recent filters like SOP, and biodegradable SPI are efficient filtering systems with unique fascinating properties of self-disinfecting and inactivation of airborne viruses finally resulting into improving IAQ.

**Challenges**

The epidemic situation of COVID-19 has greatly affected lives around the world. Contact restrictions, quarantine, and economic growth losses induce wide-range changes to the psychosocial environment throughout several countries. The present condition has affected teenagers, children, and relative families in an exceptional mode. Playgrounds and normal schools are closed, along with limited social activities and out-of-home vacation events. Parents have been helping their children with homeschooling along with the work from home. In addition to the anxieties and worries due to COVID-19, the economic shutdown has deteriorated the employment levels among all the affected countries which have further led to mental health issues and violence (Levine-Tiefenbrun et al., 2021).

**Unvaccinated community**

The ongoing mass vaccination programs curb COVID-19 infection by shielding persons against severe illness from contagious virus and probably lower the chances of spreading to another unvaccinated person. Overall, each 20% of vaccinated individuals in an assumed population, the fraction of COVID-19 positive cases for individuals who have been not vaccinated decreased almost by twofold (Team, 2020). Furthermore, as the population varies with environmental parameters and socio-behavioral even without any vaccination and since worldwide disease rates display both unvaccinated and vaccinated persons, it becomes challenging to measure the impact of vaccination on community-level SARS-CoV-2 spread. Also, it is evident that unvaccinated community are more prone to viral infection and contributes more to increased COVID-19 cases globally in comparison to the vaccinated community.

**No more social distancing**

Social distancing is an effective non-pharmaceutical strategy to reduce the infection spread of lethal viruses by keeping a suitable distance from one person to another to avoid any physical contact. During this pandemic, the lockdown has played a significant role in restricting social activities and maintaining social distancing among individuals. But this has led the people to spend more time indoors and contributed to the poor household air pollution. Due to more person density within the enclosed spaces, practicing social distancing becomes a challenge. Children and their families are failed to avoid the close contact (about 2 m) and contributing to an increased rate of COVID-19 cases and worsening the air quality as well ((COVID-19) 2021).

**Kids under 12**

Most of the kids with COVID-19 infection either have no symptoms, or exhibit mild symptoms including, fatigue, cold, and low-grade fever. Recent studies raise the concern that children also contribute to spreading infection in addition to adults. Newborn infants or babies (Fig. 7) under 1 are more prone to severe infection and are at higher risk because of their immature immunity and narrower airways making them more difficult in breathing or infants with respiratory infection system. However, most children with confirmed cases normally don’t become sick like adults while few show no symptoms at all. Additionally, kids with underlying issues like diabetes, asthma, obesity, congenital heart disease, and conditions affecting the metabolism or nervous system are also at higher risk of COVID-19 (Zivin and Sanders, 2020). Recently, the Pfizer-BioNTech COVID-19 vaccine is available under emergency use but authorized only to children ages 12 to 15 years and proved 100% effective (Team, 2020).

**Policy interventions & freedom of choice**

The COVID-19 pandemic has enforced societies to oppose what losses they are willing to make to rapidly face threats to community health. The epidemic shock is unpredictable in its rapid outbreak, but the question about employment or trade loss is not new. Environment protection regulations, state-level legislation, safety directives, and the fights against other catching illnesses all enforce both nonpecuniary and pecuniary expenses on the community to promote people’s health. However, the burden of economic loss due to restrictions imposed on social activities includes holding back human capital, falling off productivity, and contributing to a long-period drag on economic growth (Taylor et al., 2020).

**Various mutants of the covid-19 virus**

Viruses tend to create a new variant, or strain, of a virus after constantly modifying themselves through mutation. In general, the type of variant doesn’t affect the working mechanism of a virus but it might act in different ways. Recently, researchers are keeping tracking changes in the COVID-19 virus around the world which help to understand the spread and control of COVID-19 variants (Fig. 7) their health effect on the body, and the effectiveness of vaccines. When a virus has one or more new mutations it’s called a variant of the original virus. Recently, the Centers for Disease Control and Prevention has identified two variants of the virus (SARS-CoV-2) that causes coronavirus disease 2019 (COVID-19) as variants of concern. **Delta (B.1.617.2).** This variant is nearly twice as contagious as earlier variants and might cause more severe illness. The greatest risk of transmission is among unvaccinated people. People who are fully vaccinated can get vaccine breakthrough infections and spread the virus to others. However, it appears that vaccinated people spread COVID-19 for a shorter period than unvaccinated people. While research suggests that COVID-19 vaccines are slightly less effective against the delta variant, the Pfizer-BioNTech, Moderna, and Janssen/Johnson & Johnson COVID-19 vaccines still appear to protect against severe COVID-19. **Omicron (B.1.1.529).** This variant might spread more easily than other variants, including delta. But it’s not yet clear if omicron causes more severe disease. It’s expected that people who are fully vaccinated likely can get breakthrough infections and spread the virus to others. However, the COVID-19 vaccines are expected to be effective at preventing severe illness. This variant also reduces the effectiveness of some monoclonal antibody treatments.
The alpha, gamma, and beta variants continue to be monitored but are spreading at much lower levels in the U.S. The mu variant is also being monitored.

Whether the full set of profits offset the price in any specific event depends on a host of condition-specific parameters, involving the nature of the health hazard and the usefulness and cost of the strategy intended to restrict it. A recent report by Taylor and co-researchers revealed that the noteworthy costs acquired from a continuous procedure of meat-packing business estimated “essential businesses” during the epidemic situation and this business have potentially contributed to the transmission of COVID-19 both within the urban areas and local communities (Greenhalgh et al., 2021).

5. Discussions

Owing to the widespread of SARS-CoV-2, several disinfectants have been applied for indoor environment safety in homes and denser public places including health centers, schools, colleges, and workplaces as strong cleaning protocols during a covid pandemic (Yu et al., 2004; Nissen et al., 2020). In general, the disinfecting agents contain quaternary ammonium materials (QAMs) as proved by the CDC, the United States for specific interaction with the SARS-CoV-2 virus (Ferguson et al., 2020). The QAMs are quaternary ammonium salts having a hydrophobic substituent and short-chain groups as methyl or benzyl along with various microbes or disinfectants for skincare materials, cleaning products, and biomedical products (Li et al., 2007; Jones et al., 2020). The Queen Anne’s Country (QAC) groups might be classified in benzylalkyl-dimethylammonium (C6–C18 alkyl chains) based materials, dialkyl-dimethylammonium (C8–C18 alkyl chains) based materials and alkyltrimethyl ammonium (C8–C18 alkyl chains) based materials (Li et al., 2007). In living beings, the QAMs might damage cell membranes of adipose tissue as well as the viral envelopes to extract organic materials which make them act like disinfectants or antimicrobials (Jones et al., 2020). However, QAMs as asthmagens, might enhance asthma-related breathing problems, such as inflammation or deteriorate pulmonary cells, skin irritation, and low fertility rates (Jones et al., 2020; G. Buonanno et al., 2020). In addition, prolonged use of QACs might damage the lipid membranes of the skin resulting in high absorption of toxic compounds, and improving the permeability of outer membranes of living organisms, thus growing concern for excessive use of QAMs as well (G. Buonanno et al., 2020; Lelieveld et al., 2020). Hence, QAMs have been obtained from food additives, fruits, dairy products or milk, wastewater sludge, surface waters, sediments, and soil as well (G. Buonanno et al., 2020; Peng and Jimenez, 2021; Thatcher et al., 2002). However, QAMs prefer to be adsorbed on solid particles and dust particles due to their low volatility leading to long-term indoor contamination.

Airborne contaminants

The part of the environmental air which is considered foreign particles to the normal state of the atmosphere air is categorized as airborne contaminant materials. Such air contaminants might be majorly originated from human daily activities and provides an irritating and detrimental effect on living beings (G. Buonanno et al., 2020). Furthermore, industrial activities play a major role in various man-made contaminants into the atmosphere. Such contaminants might be found in all states of matter as gas, vapor, or solid and PM including mists, fumes, and dust particles which move in to air as aerosol or solid particles (Peng and Jimenez, 2021). COVID-19 outbreak situation has provided an unprecedented influence on various parameters like human health, economy, lifestyle, and environment. This epidemic has raised certain questions, including its beginning source, affecting factors, curing remedies, and preventive steps for a sustainable future (Thatcher et al., 2002). In con-
junction with humidity and temperature, air quality is one such factor that has a co-relation with both resident health in indoor spaces and COVID-19. The indoor airborne contaminants are mostly composed of NO2 and PM2.5 particles that worsen the exposure to COVID-19 infection (Ninomura and Bartley, 2001).

Air quality index

The index for calculating the quality of atmosphere air on daily basis is called the air quality index (AQI). In general, it is a measurement of air pollution level for its health effects at a particular time. AQI is considered the most crucial point that helps individuals to estimate the prevailing situation of air quality. The increased AQI value indicated escalating contaminant concentration which circuitously strengthened the prevailing epidemic (Ma et al., 2021). The contaminants increase in an enclosed environment on account of socio-cultural activities in addition to temperature and related humidity of accustomed space and usual climatic changes. Consequently, the indoor atmosphere can be degraded if sufficient ventilation is not available, advising exploring the good control technologies for increasing the AQI to achieve a sustainable future for society (Barcelo, 2020). The new engineering methods provided in this review article covered mostly non-pharmaceutical sustainable solutions including, social distancing, ventilation, inside plating, wearing facemasks, etc. These emerging controls have assisted immensely in falling down the increased rate of confirmed infected cases.

Conclusions and recommendations

The SARS-CoV-2 is highly contagious and lethal in association with aerosols coming from talking, coughing, and sneezing. Coronavirus transmission has been considered aerosol transmission which supports treatments because the virus might remain viable ~3 h in aerosols. In indoor applications, air conditioning, heating, and ventilation has been considered as a primary source to spread the virus. To tackle this pandemic, it should be applied in an efficient and correct way to prevent the transmission or spread of the virus via airborne sources as proposed in earlier reports for coronavirus. Exposure to indoor air pollution particularly PM2.5 and NO2 may enhance the vulnerability to infection and mortality from a virus. Some studies also reported that exposure to air contamination may influence the transmissible infection of COVID-19. The available research studies in this field might help the epidemiologists in selecting appropriate steps to prevent such a pneumonia type epidemic in the future. The present review provides a general state of art involving the role of air pollution, especially in PM10, PM2.5, and NO2, in COVID-19 infection and lethality. Herein, a variant good control strategies for indoor air purification and sufficient ventilation is suggested. These air purification technologies have proved potential enough to improve residential health and protection from contagious aerosolized particles. In addition, the challenges faced by humans staying indoors during this epidemic situation along with preventive sustainable solutions are discussed. Researchers should attain their attention to the poor or unvaccinated communities, who are more susceptible to indoor airborne pollution and high infectious risk of COVID-19. Moreover, the air quality index must be considered utmost part of a united strategy for public health prevention and protection from the transmission of a pandemic. Our recommendation for further research is directed towards the investigation of indoor-outdoor air exchange measures, routes of airborne transmission, and physiochemical or biological characteristics of virus-laden aerosols. Inclusively, it can be noticed that the given solutions are limited as per the condition required and the implication of either one or two measures may not help in curbing the COVID-19 cases. But, following these approaches altogether could prove an effective solution to combat the current epidemic and prevent a similar state in the future.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Wang, C., Horby, P.W., Hayden, F.G., Gao, G.F., 2020. A novel coronavirus outbreak of global health concern. Lancet 395, 470–473.
Zhu, N., Zhang, D., Wang, W., Li, X., Yang, B., Song, J., Zhao, X., Huang, B., Shi, W., Lu, R., 2020. A novel coronavirus from patients with pneumonia in China, 2019. N. Engl. J. Med.
Zaki, A.M., Van Boeheim, S., Bestebroer, T.M., Osterhaus, A.D., Fouchier, R.A., 2012. Isolation of a novel coronavirus from a man with pneumonia in Saudi Arabia. N. Engl. J. Med. 367, 1814–1820.
Kahn, J.S., McIntosh, K., 2005. History and recent advances in coronavirus discovery. Pediatr. Infect. Dis. J. 24, S223–S227.
Bhatia, S., Imai, N., Cuomo-Dannenburg, G., Baguelin, M., Boonyasiri, A., Cori, A., Cucunуба, Z., Dorigatti, I., FitzJohn, R., Fu, H., 2020. Report 6: relative sensitivity of international surveillance. Imperial College London COVID-19 Response Team.
Patal, S., Kumar, A., Raizada, P., Van Le, Q., Selvasameth, R., Singh, P., Thakur, S., Hussain, C.M., 2022. Potential of graphene based photocatalyst for antiviral activity with emphasis on COVID-19: a review. Environ. Chem. Eng. Mech. 107527.
Xu, Z., Shi, L., Wang, Y., Zhang, J., Huang, L., Zhang, C., Liu, S., Zhao, P., Liu, H., Zhu, L., 2020. Pathological findings of COVID-19 associated with acute respiratory distress syndrome. Lancet Respir. Med. 8, 420–422.
Lu, R., Zhao, X., Li, J., Niu, P., Yang, B., Wu, H., Wang, W., Song, H., Huang, B., Zhu, N., 2020. Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet 365, 565–574.
Fehr, A.R., Perlman, S., 2015. Coronavirus: an overview of their replication and pathogenesis. Coronavirus 1–23.
Zhou, P., Yang, X.-L., Wang, X.-G., Hu, B., Zhang, L., Wang, Z., Si, H.-R., Zhu, Y., Li, B., Huang, C.-L., 2020. A pneumonia outbreak associated with a new coronavirus of probable bat origin. Nature 579, 270–273.
Kim, D., Lee, J.-Y., Yang, J.-S., Kim, J.W., Kim, V.N., Chang, H., 2020a. The architecture of SARS-CoV-2 transcriptome. Cell 181, 914–921.
Jungreis, I., Sealoff, R., Kellis, M., 2021. SARS-CoV-2 gene content and COVID-19 mutation impact by comparing 44 Sarbecovirus genomes. Nat. Commun. 12, 1–20.
Stewart, H., Brown, K., Dinan, A.M., Irving, N., Snijder, E.J., Firth, A.E., 2018. Transcriptional and translational landscape of equine torovirus. J. Virol. 92, 589–518.
S. Yi, In Encyclopedia of the Human Genome (ed D.N. Cooper) Nature Publishing Group, (2003).
Akashi, H., 1994. Synonymous codon usage in Drosophila melanogaster: natural selection and translational accuracy. Genetics 136, 927–935.
Chamary, J.-V., Parmley, J.L., Hurst, L.D., 2006. Hearing silence: non-neutral evolution at synonymous sites in mammals. Nat. Rev. Genet. 7, 98–108.
Nei, M., 1987. Molecular Evolutionary Genetics. Columbia university press.
Yang, X., Wu, C., Li, X., Song, Y., Yao, X., Wu, X., Duan, X., Zhang, H., Wang, Y., Qian, Z., 2020a. On the origin and continuing evolution of SARS-CoV-2. Nat. Sci. Rev. 7, 1012–1021.
Boni, M.F., Lemey, P., Jiang, X., Lam, T.T.-Y., Perry, R.W., Castoe, T.A., Rambaut, A., Robinson, D.L., 2020. Evolutionary origins of the SARS-CoV-2 sarbecovirus lineage responsible for the COVID-19 pandemic. Nat. Microbiol. 5, 1408–1417.
Li, X., Zai, J., Zhao, Q., Nie, Q., Li, Y., Fodey, B.T., Chaillon, A., 2020. Historical evolution, potential intermediate animal host, and cross-species analyses of SARS-CoV-2. J. Med. Virol. 92, 602–611.
Chaw, S.-M., Tai, J.-H., Chen, S.-L., Hsieh, C.-H., Chang, S.-Y., Yeh, S.-H., Yang, W.-S., Chen, P.-J., Wang, H.-Y., 2020. The origin and underlying driving forces of the SARS-CoV-2 outbreak. J. Biomed. Sci. 27, 1–12.
Dabrovolski, S.A., Kovalnokov, Y.K., 2020. SARS-CoV-2: structural diversity, phylogeny, and potential animal host identification of spike glycoprotein. J. Med. Virol. 92, 1690–1694.
Gao, Y.-R., Cao, Q.-D., Hong, Z.-S., Tan, Y.-Y., Chen, S.-D., Jin, H.-J., Tan, K.-S., Wang, D.-Y., Yan, Y., 2020. The origin, transmission and clinical therapies on coronavirus disease 2019 (COVID-19) outbreak—an update on the status. Mil. Med. Res. 7, 1–10.
Rangsayasami, A., Kannan, K., Murugesan, S., Radhika, D., Sadasivuni, K.K., Reddy, K.R., Raghu, A.V., 2021. Influence of nanotechnology to combat against COVID-19 for global health emergency: a review. Sensors International 2, 100079.
Cai, J., Li, F., Shi, Z.-L., 2019. Origin and evolution of pathogenic coronaviruses. Nat. Rev. Microbiol. 17, 181–197.
Pirouz, B., Arcuri, N., Pirouz, B., Palermo, S.A., Turco, M., Maiolo, M., 2020. Development of an assessment method for evaluation of sustainable factories. Sustainability 12, 1841.
Ogut, O., 2020. Laboratory biosafety guidance related to coronavirus disease 2019 (COVID-19): interim guidance, 12 February 2020. World Health Organization.
Shafiee Haghsenas, S., Pirouz, B., Shafiee Haghsenas, S., Pirouz, B., Pirouz, P., Na K.-S., Cho, S.-E., Geem, Z.W., 2020. Prioritizing and analyzing the role of climate and urban parameters in the spread of COVID-19 based on artificial intelligence applications. Int. J. Environ. Res. Public Health 17, 3730.
CSSE, Coronavirus COVID-19 Global Cases By the Centre For Synthesis Science and Engineering (CSSE), at Johns Hopkins.
Stadnytskyi, Singh, Dong, S.P., Patial, BMC Sustain. Infect. 48, 1–100.

J. S., Singh, W., Bashir, S., Knowles, S., Alhasa, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.

J.S., Bashir, A., SARS-CoV-2, 2015.
Taylor, C.A., Boulon, C., Almond, D., 2020. Livestock plants and COVID-19 transmission. Proc. Natl. Acad. Sci. 117, 31706–31715.

Greenhalgh, T., Jimenez, J.L., Prather, K.A., Tulecki, Z., Fisman, D., Schooley, R., 2021. Ten scientific reasons in support of airborne transmission of SARS-CoV-2. Lancet 397, 1603–1605.

Yu, I.T., Li, Y., Wong, T.W., Tam, W., Chan, A.T., Lee, J.H., Leung, D.Y., Ho, T., 2004. Evidence of airborne transmission of the severe acute respiratory syndrome virus. N. Engl. J. Med. 350, 1731–1739.

Nissen, K., Krambrich, J., Akaberi, D., Hoffman, T., Ling, J., Lundkvist, Å., Svensson, L., Salanek, E., 2020. Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards. Sci. Rep. 10, 1–9.

Ferguson, N., Taylor, J., Davies, M., Shrubsole, C., Symonds, P., Dimitroulopoulou, S., 2020. Exposure to indoor air pollution across socio-economic groups in high-income countries: a scoping review of the literature and a modelling methodology. Environ. Int. 143, 105748.

Li, Y., Leung, G.M., Tang, J., Yang, X., Chao, C., Lin, J.Z., Lu, J., Nielsen, P.V., Niu, J., Qian, H., 2007. Role of ventilation in airborne transmission of infectious agents in the built environment—A multidisciplinary systematic review. Indoor Air 17, 2–18.

Jones, N.R., Qureshi, Z.U., Temple, R.J., Larwood, J.P., Greenhalgh, T., Bourouiba, L., 2020. Two metres or one: what is the evidence for physical distancing in covid-19? BMJ 370.

Buonanno, G., Morawska, L., Stabile, L., 2020a. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications. Environ. Int. 145, 105794.

Lelieveld, J., Helleis, F., Bormann, S., Cheng, Y., Drewnick, F., Haug, G., Klimach, T., Sciare, J., Su, H., Pöschl, U., 2020. Model calculations of aerosol transmission and infection risk of COVID-19 in indoor environments. Int. J. Environ. Res. Public Health 17, 8114.

Buonanno, G., Stabile, L., Morawska, L., 2020b. Estimation of airborne viral emission: quanta emission rate of SARS-CoV-2 for infection risk assessment. Int. Environ. Res. Public Health 17, 105794.

Peng, Z., Jimenez, J.L., 2021. Exhaled CO2 as a COVID-19 infection risk proxy for different indoor environments and activities. Environ. Sci. Technol. Lett. 8, 392–397.

Thatcher, T.J., Lai, A.C., Moreno-Jackson, R., Sextro, R.G., Nazaroff, W.W., 2002. Effects of room furnishings and air speed on particle deposition rates indoors. Atmos. Environ. 36, 1811–1819.

Ninomiya, P., Bartley, J., 2001. New ventilation guidelines for health-care facilities. ASHRAE J. 43, 29.

Ma, J., Qi, X., Chen, H., Li, X., Zhang, Z., Wang, H., Sun, L., Zhang, L., Guo, J., Morawska, L., 2021. Coronavirus disease 2019 patients in earlier stages exhusted millions of severe acute respiratory syndrome coronavirus 2 per hour. Clin. Infect. Dis. 72, 652–654.

Barcelo, D., 2020. An environmental and health perspective for COVID-19 outbreak: meteorology and air quality influence, sewage epidemiology indicator, hospitals disinfection, drug therapies and recommendations. J. Environ. Chem. Eng. 8, 104006.