https://doi.org/10.48048/tis.2024.8287

Role of Fluid Dynamics in Infectious Disease Transmission: Insights from COVID-19 and Other Pathogens

Soumyajit Koley

Department of Civil Engineering, Hooghly Engineering & Technology College, West Bengal, India

(Corresponding author's e-mail: samkoley5@gmail.com)

Received: 8 April 2024, Revised: 18 May 2024, Accepted: 25 May 2024, Published: 1 June 2024

Abstract

The spread of infectious diseases such as COVID-19 depends on complex fluid dynamics interactions between pathogens and fluid phases, including individual droplets and multiphase clouds. Understanding these interactions is crucial for predicting and controlling disease spread. This applies to human and animal exhalations, such as coughs and sneezes, as well as bursting bubbles that create micron-sized droplets in various indoor and outdoor environments. By exploring case studies in this regard, this study examines the emerging field of fluid dynamics in disease transmission, focusing on multiphase flows, interfacial flows, turbulence, pathogens, human traffic, aerosol transmission, ventilation, and breathing microenvironments. These results indicate that increased ventilation rates and local ventilation methods can effectively reduce the concentration of SARS-CoV-2-laden aerosols in the immediate breathing spaces between individuals. In a displacement-ventilated room, both neutral and unstable conditions were more effective in removing breathed SARS-CoV-2-laden aerosols from the air, regardless of the presence of test subjects. However, stable conditions may increase the risk of infection in individuals living in confined spaces. Thus, the findings of this study are useful for providing practical guidance for managing the spread of airborne infections.

Keywords: Multiphase flows, Interfacial flows, Turbulence, Pathogen, Human traffic, COVID-19, Aerosols transmission, Ventilation, Breathing microenvironment

Introduction

The catastrophic COVID-19 pandemic has demonstrated how local outbreaks can quickly escalate and place a strain on national healthcare systems and the global economy, resulting in significant financial costs surpassing those of earlier influenza pandemics [1]. This highlights the urgent need for science-based research focusing on prevention, infection control, and pre-drug/vaccine illness management [2]. During an epidemic, crucial considerations centre on how the disease spreads and the approach to containment and prevention [3]. The spread of SARS-CoV-2 and safeguarding healthcare personnel and the most vulnerable populations during shortages of masks or respirators are pertinent questions [4]. Additionally, the recommended frequency and method for decontaminating hospital rooms, airlines, cruise ships, and dormitories, as well as the recommended distance between persons for activities such as breathing, speaking, singing, coughing, and sneezing, are all relevant considerations [5]. The use of masks for source control is a vital aspect to consider [6]. These questions are relevant not only during a global pandemic but also in the context of seasonal influenza, which causes approximately 500,000 deaths annually worldwide, and tuberculosis, which claims over 1,000,000 lives each year and is the primary cause of death from an infectious disease [7]. Recent research on infectious diseases on a small spatial scale has made significant progress in understanding pathogen–host invasion, infectious disease pathophysiology, and host immunology [8]. Detailed spatiotemporal data and models were created to anticipate the spread of epidemics across regions and countries on a broad scale. However, there is still a significant lack of knowledge on disease transmission at the intermediate level, where transmission between hosts serves as a connection between pathogen-host interactions and host physiology, environmental factors, and broader population dynamics [9]. A transmission event may seem too short and random to be controlled by identifiable underlying processes that can be utilised for intervention [10]. Therefore, it is essential to invest in research to better understand and manage the spread of infectious diseases. The transmission of infections from one host to another is a vital aspect of their lifecycle [11]. Therefore, to survive, infections must adapt to the process of suspension and interaction with fluids [12]. It is crucial to investigate the impact of fluids on the transmission and spread of diseases and how viruses modify their behaviour to ensure their survival during the transmission process [13]. **Table 1** lists all notations defined in this article. Machine learning techniques (elaborated in subsequent sections below) were explored in this study to determine the role of quantitative methods in augmenting the simulation efficacy of prevalent computational fluid dynamics models in estimating transmission pathways of infectious airborne diseases.

Materials and methods

Historical discourse

Daniel Bernoulli, renowned for his work in hydrodynamics, initially pursued a medical education and earned his degree from the University of Basel in 1721 with a thesis titled Dissertatio physico-medica de respiratione [14]. He subsequently transitioned from being a professor of anatomy and botany to a professor of physics [15]. The individual pioneered the application of probabilistic modelling in epidemics to assess the efficacy of variolation against smallpox and predict the potential increase in life expectancy following the eradication of smallpox [16]. He was the first physicist to engage in epidemiology formally [17]. Until the eighteenth century, there was a prevalent belief that contagious illnesses were spread by inhaling harmful fumes known as miasma, which originated from decaying substances [18]. The main argument focuses on the origin and spontaneous development of the infectious pathogens. The notion of transmitting disease-causing pathogens gained popularity in the late 19th century [19]. Experiments conducted by Pasteur in 1861 and Koch in 1876 on anthrax, TB, and cholera strongly support the germ hypothesis by demonstrating that certain microbes are responsible for causing infectious illnesses [20]. Argyropoulos *et al.* [21] showed that pathogens in exhaled droplets can settle around an infected person, leading to the belief that direct contact with these droplets was the main way respiratory diseases spread until the 1930s [22]. Debates, contradicting methods, and ad hoc attempts for answers arise because of the absence of a mechanistic explanation of the intermediate transmission size [23].

Debates over the transmission channels of healthcare-associated diseases mainly focus on surface cleaning as a way to prevent infections while often ignoring or rejecting the importance of air contamination and persistence of airborne pathogens [24]. In the field of agriculture and food safety, there is limited understanding of the transmission of pathogens to plants or produce, which contributes to ongoing productivity loss due to insufficient prevention and management of cross-contamination [25]. At this intermediate scale, a thorough comprehension of the underlying mechanisms can drive advancements in non–pharmacological and pharmacological interventions as well as epidemic control techniques [26]. Fluids are prevalent in intermediate sizes [27]. Exhaled droplets can remain suspended in the air for extended periods, which is influenced by the surrounding temperature and humidity levels [28]. These droplets can spread by bursting bubbles or splashing from moist contaminated surfaces [29]. Detailed knowledge of the fundamental fluid dynamics involved is crucial for simulating and predicting the transmission of infectious diseases across hosts [30]. proposed a methodology to simplify and analyse complex transmission events into manageable, biophysically based mechanistic processes, following the advice of Bernoulli [31].

Previous studies have demonstrated that the CONTAM multizone contaminant transportation model effectively forecasts the airflow/ventilation and pollutants [9-19]. These verifications have primarily aimed to utilise the CONTAM-quanta model to analyse the superspreading incident related to the Skagit Valley Chorale and then contrast the findings with the COVID-19 Aerosol Transmission Estimator [7]. The quanta transmission was analysed using the single-zone CONTAM scenario FaTIMA [8]. The primary goal of the FaTIMA program is not to analyse aerosols at the quantum level but to model the transmission of infectious particles. The investigation confirmed the effectiveness of the proposed CONTAM quanta method in this part of the FaTIMA. The numerical strategy was verified by comparison with a previous analytical method that utilised the same input parameters. It is essential to verify that the numerical programming of the software tool aligns with the results reported in the literature to confirm a close match between the calculated and expected values of airborne concentrations obtained using the COVID-19 Aerosol Transmission Estimator approach. The final aerosol levels in the air were determined to be 0.56 quanta m^3 in both studies. After 2 h, the exposure risk is 88.6 %. The suggested CONTAM-quanta method can produce exposure assessment findings similar to those of prior research. This was a comparison between the CONTAM multizone and single-zone FaTIMA simulations in relation to the baseline scenario (Baseline OA + MERV8). The central Variable Air Volume (VAV) ventilation system in the large office, together with air leaks, facilitated the passage of air across zones, leading to the observed discrepancies. The single-zone FaTIMA model can only manage steady weather conditions, whereas the multizone model utilises Chicago TMY3 meteorological data. The CONTAM simulation imitated the VAV systems in a Large Office building by utilising a series of air-handling units on several levels, more accurately replicating aerosol transmissions through return grills and other multizone systems. For comparison, FaTIMA uses a singular fundamental supply/return mechanism. The CONTAMquanta technique was compared to 3 existing models: FaTIMA, the COVID-19 estimator for single zones, and the REHVA Calculator for multizones, as shown in **Tables 2** and **3**.

Recent developments

The study of fluid dynamics in disease transmission aims to elucidate the fundamental mechanisms that influence the spread of pathogens through various processes, including droplets, bubbles, and complex flows [32]. The term ‘health’ is defined expansively to encompass human, plant, and animal populations [33]. Disease transmission in these populations is influenced by a complex series of fluid dynamics and biophysical processes that affect pathogen release, spread, survival, and infection of new hosts [34]. To fully comprehend the entire transmission process, it is necessary to analyse the fundamental physics involved, especially the complex fluid dynamics at different scales and phases, and how they interact with the pathogen [35]. proposed a paradigm centred around certain physical stages that influence transmission and survival [36]. Phase 1 involves the extraction and encapsulation of pathogens within the host [37]. Phase 2 includes the release and transportation of pathogens from the host [38]. Phase 3 focuses on the ecology and longevity of pathogens in the environment, and Phase 4 of the transmission framework deals with the infiltration and infection of new hosts [39]. This review examined this framework in relation to respiratory and nosocomial infections, water-to-air pathogen transfer, and pathogen transmission in agriculture [40]. Finally, we summarise the existing knowledge gaps and potential research opportunities in the fluid and health fields [41]. The COVID-19 pandemic has led to unprecedented containment measures worldwide to control SARS-CoV-2 transmission [42]. Since the initial reports of a novel infectious disease outbreak in the Chinese province of Hubei, public health experts have investigated the transmission of this new virus [43]. As of July 2020, the transmission mechanism of SARS-CoV-2 remains debatable [44]. Moreover, the transmission methods of the most prevalent respiratory illnesses are not well understood [45]. In this study, we investigated the mechanisms by which exhalations carry respiratory pathogens through fluid dynamics [46]. Exhalations such as breathing, talking, laughing, coughing, sneezing, and singing were included in Phase 2 of the transmission framework [47]. It is now recognised that all of these entail the release of a gas phase containing droplets of various sizes [48]. The velocity, total volume, and liquid volume portions of these emissions generate the spatiotemporal probability density function of contamination in air and on surfaces, referred to as the ‘pathogen footprint’ [49]. In the early twentieth century, it was believed that most respiratory infectious diseases spread through direct contact with visible droplets generated by infected individuals [50]. Despite the prevalence of various interpretations of disease transmission across different professions, a clear and universally understood definition is necessary, particularly during global pandemics [51]. This is to prevent confusion in scientific research, the media, and public health policies [52]. In this review, a ‘droplet’ is defined as a liquid fluid, while ‘droplet nuclei’ refer to the solid remaining after the liquid has dried, forming a complex solid residue [53]. Both droplets and droplet nuclei can remain suspended in air and act as vehicles for disease transmission [54]. However, the term ‘aerosol’ encompasses all types of materials suspended in the air, which is different from droplets [55]. Airborne transmission in infectious disease control is defined as the spread of either airborne droplet nuclei or tiny particles within a respirable size range containing infectious agents, which appears to exclude droplets from the definition [56]. It is crucial to establish a universal definition based on precise physical composition to avoid confusion [57]. Notably, no dry nuclei or residues were released from infected hosts [58]. Therefore, a physics-based division emerged that categorised respiratory transmission as either big or not [59]. small droplet pathways or droplets against aerosols based on the initial droplet size [60]. In conclusion, a clear and globally understood definition of droplets and aerosols is essential to prevent confusion in scientific research, media, and public health policies during a pandemic [61].

According to the findings of [62], large droplets tend to fall close to the person inhaled, whereas smaller droplets evaporate and become flying droplet nuclei [63]. Ambient airflow can transport droplet nuclei over short distances at a rate of centimetres per second, primarily in indoor environments [64]. The maximum distance travelled by droplet nuclei is primarily regulated by the weak advective flows of ventilation and climate control systems in indoor environments, rather than by the emission dynamics of activities such as speaking, coughing, or sneezing [65]. The distinction between large and small droplets remains crucial in classification systems of organisations such as the World Health Organization (WHO) and the Centers for Disease Control and Prevention (CDC) [66]. Several experimental methods used to measure droplet size distributions have yielded conflicting results [67]. These methods include droplet counting on glass slides, aerodynamic droplet sizing, interferometric Mie imaging, droplet image velocimetry, low-pressure electric impactor spectrometry, scanning mobility droplet sizing, and laser diffraction [68]. Various instruments and calibrations are associated with these methods, often requiring assumptions about the optical characteristics, evaporation rates, morphologies, sphericity, and compactness of droplets or particles [69]. Determining the properties of droplets composed of complex biological fluids or components is challenging, resulting in highly variable measurements [70]. These methods exhibit different sensitivities across different sizes, are not standardised to a common reference range, and often only analyse a small sample volume, which can increase background noise [71]. Droplet sizes are typically determined at a single remote sample point and are significantly influenced by environmental factors such as humidity and temperature, which present a fundamental issue of under-sampling in both spatial and temporal dimensions, especially when attempting to accurately capture fleeting and irregular emissions [72]. It is crucial to determine whether pathogens are present and remain infectious or reside in droplets based on their size as well as the droplet sizes themselves [73]. The outcome is influenced by the volume of droplets collected, methods of handling, and techniques used for amplification [74].

An understanding of the fluid fragmentation processes that create droplet sizes and speeds complements the improvement of measurement techniques by establishing expected limits and physical constraints on the range of droplet sizes and speed distributions in physiological fluids [75]. This has been utilised and discussed in the current COVID-19 situation, similar to its use during the SARS outbreak [76]. Researchers have been intrigued by the size distribution of expelled droplets based on several types of expiration, including breathing, speaking, coughing, and sneezing [77]. Therefore, infection control professionals should focus on establishing whether a pathogen is primarily transmitted by droplets or aerosols when a new respiratory infectious illness arises [78]. Two issues arise with this technique, prompting the need to reject inaccurate droplet versus aerosol transmission classifications [79]. Public health authorities mostly attempt to deduce the main pathways of disease transmission using extensive population epidemic data, which are constrained by various restrictions, scarcity, and underreporting [80]. The spread of infectious diseases within households can be attributed to various transmission pathways [81]. The lack of comprehensive epidemiological data makes it difficult to distinguish between different transmission routes [82]. To gain a better understanding of the dominant transmission processes and underlying principles, intermediate-scale investigations are essential [83]. This is particularly relevant in indoor environments, where transmission can occur through both large and small drops [84]. The contrast between Wells' static perspective and dynamic cloud evolution view is not merely theoretical [85]. The gas cloud expands the range of droplets of all sizes by capturing and transporting them further than if they were released as individual droplets in still air [86]. Moist exhaled gas can protect droplets from evaporation in cold and dry outside air, which is distinct from warm and humid conditions within the respiratory system [87]. This, coupled with cloud momentum, facilitates the extension of the range of all droplet sizes [88]. The fluid dynamics of exhaled multiphase turbulent puff clouds have significant implications for safety measures, physical/social distancing, respiratory protection of healthcare workers, and indoor air hygiene [89]. Public health policymakers are currently addressing these pressing issues owing to the lack of previous research investment in these areas [90].

Table 1 List of abbreviations and notations used in this study.

ϕ	Laplace limit
ψ	Time series of observation data
ф	Time series of model data
ρ_ϕ	Eigen function for Fourier transform of reflectivity
ν_ϕ	Eigen function for Fourier transform of absorptivity
Ƙ	Lagrange polynomial multiplier
Þ	Flajolet-Odlyzko constant
Ḧ	Vandermonde polynomial multiplier
ξ	Khinchin-Lévy constant
Ʈ	Dirichlet integral of temperature
Ḡ	Dirichlet integral of discharge
η	Oscillatory integral operator for inflow

μ	Oscillatory integral operator for turbulence
ϒ	Mean squared deviation
Ü	Dirichlet integral of transmissivity
ζ	Riemann zeta function representing Dirichlet series
θ	Lemniscate constant representing the integral covariance of stochastic data
α	Peak frequency density of observation data
β	Peak frequency density of model data
Ω_θ	Hyper-harmonic median of Dirichlet series
λ_α	Peak wavelength density of observation data
λ_β	Peak wavelength density of model data
ω_n	Sylvester sequence of Eigen solutions
Ѵ	Taylor series expansion derivative
Ṝ	Maclaurin series expansion derivative
f	Bessel corrected variance
σ_ϕ	Fourier integral of feedback components
χ	Bernoulli continuity coefficient for Gregory’s series
$Б_\tau$	Recursive Bayesian Estimation of relative conjugate error

Latest case studies

The formation of droplets in the respiratory tract is a complex process that involves the expulsion of mucosalivary fluid or creation of droplets through a combination of shear and film rupture instabilities [91]. These droplets can form sheets that stretch and break into rings and fluid ligaments, eventually forming droplets in the turbulent gas phase [92]. The destabilisation of these droplets is influenced by combinations of Kelvin-Helmholtz, Rayleigh-Plateau, and Rayleigh-Taylor instabilities, which are driven by the surface tension, viscous forces, and aerodynamic forces [93]. The proportions of these forces dictate the fragmentation patterns and the resulting size and speed distributions of droplets in exhaled turbulent puff clouds [94]. Mucosalivary ligaments are strained by the underlying fluctuating turbulent flow [95]. Viscous effects are minimal compared to inertial and surface tension effects in emissions; however, they may be significant in individuals with respiratory diseases [96]. It is anticipated that the viscosity effect is the primary factor influencing pure mucus located deeper in the airways [97]. It is likely that the impact of this factor will change depending on the progression and type of infection, indicating a mutual interaction between the pathogen and the fluid phase [98]. In respiratory diseases, the creation and release of mucosalivary droplets in a turbulent gas cloud, along with their changes due to evaporation and condensation in the environment, make up phases 1 - 3 of the framework [99]. These phases are crucial for determining the characteristics of droplets or droplet nuclei that can be inhaled by a potential host (phase 4) [100]. The size and nature of inhaled particles affect how far they can travel in the environment and how deeply they can penetrate the respiratory system [101]. The size, content, and pathogen load of inhaled droplet nuclei define the specific lung tissue that they reach from the upper airways to the alveoli [102]. Research on animals has shown that inhalation of an atomised solution leads to greater infection and mortality rates than dry intranasal inoculation when exposed to the same amount of virus [103]. Research has examined the physics of deposition in the respiratory tract concerning medication transport and dosimetry of nebuliser treatments, as mentioned in reviews [104]. There are still significant areas of study that need to be explored regarding the deposition and penetration of respiratory contaminated droplet residues throughout phases 1 - 3 of the transmission process [105]. There are still significant questions regarding how transmission physics, complex biochemistry, and host immunology interact with the mucous barrier of the upper airway [106]. This barrier is crucial in defending against respiratory infectious agents, where the characteristics of pathogen-laden droplets from Phases to 1-3 play a role in determining the success of host cell infiltration and infection [107].

Table 2 Comparison of prevalent modelling techniques for simulating airborne aerosols' behaviour.

	COVID-19 estimator [26]	**REHVA calculator [53]**	**FaTIMA [37]**	**CONTAM [49]**	**CONTAM-quanta [56]**
Building details	-	-	-	✓	✓
HVAC details	-	-	✓	✓	✓
Occupancy schedule	-	-	-	✓	✓
Weather impacts	-	-	-	✓	✓
Multi–zone analysis	-	-	-	✓	✓
Occupant exposure	✓	✓	✓	✓	✓
Infection risk	✓	✓	-	-	✓

Stochastic integrations

Puffs, jets, thermals, and plumes are turbulent fluid bodies emitted from a single source, either continuously (jets and plumes) or discontinuously (puffs and thermals) [108]. Thermals and plumes are powered by buoyancy, while puffs and jets are propelled by momentum [109]. turbulent point-source theory effectively represents the important characteristics of geophysical and environmental processes at different scales [110]. The entrainment concept has been used to explain the dynamics of intense exhalation in detail and with precise measurement [111]. These 2 phases of cloud development are significant [112]. The first phase is characterised by a short-lived jet-like motion, including the high-momentum expulsion of the exhaled gas cloud together with its mucosalivary content [113]. In a homogenous environment, such as interior spaces with standard ceiling heights and mixed ventilation, buoyancy remains constant [114]. Even if it initially seems insignificant, buoyancy may eventually impact the path of the cloud when the forward speed decreases significantly [115]. When the speed of the cloud decreases significantly, the droplets and nuclei can be carried by the surrounding ventilation flows, which usually move at a rate of millimetres per second [116]. This transport may persist for hours to days until the particles settle on the surface or are removed via interior air circulation [117].

Alqarni *et al.* [15] introduced an advanced model to explain the settling of particles in turbulent fluid in a confined container [118]. This theoretical model is closed, meaning that it does not include any free parameters and can track the spatial and temporal changes in a gas cloud during regular exhalations, coughs, and sneezes [119]. It also measures the quantity and size of the droplets dispersed from the cloud over time and the distance from the origin [120]. This information is crucial for calculating the pathogen footprint and conducting risk-map evaluations of contamination [121]. The projected development of the cloud was verified through comparisons with similar laboratory and human subject tests [122]. The traditional approach of dichotomising transmission, inspired by Wells in the 1930s, fails to account for the presence of an exhaled multiphase gas cloud [123]. This outdated perspective is insufficient for predicting the extent of surface and air pollution caused by exhalations, necessitating a significant change in how this phenomenon is viewed [124]. By transitioning from the concept of isolated droplet emissions to the turbulent multiphase puff cloud model, we can gain a new perspective on how pathogens spread in indoor environments over time and space [125]. This shift can help assess the effectiveness of interventions related to indoor space management and occupancy by focusing on the air and surface contamination levels [126]. All exhalations, such as breathing, sneezing, coughing, talking, and singing, can be described as point-source emissions of a turbulent multiphase gas cloud containing respiratory liquid droplets [127]. The motion that propels this cloud is primarily driven by the gas phase rather than the liquid-droplet phase [128].

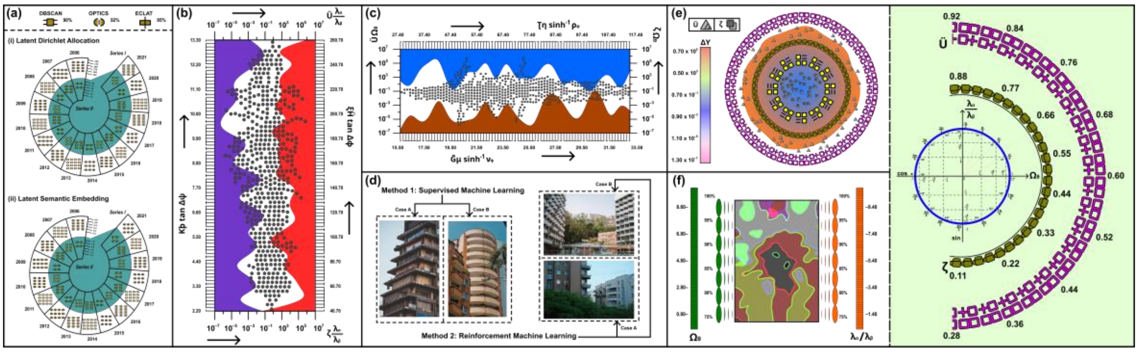

Figure 1 (a) Differential allotment of apriori machine learning algorithms across 2 separate scenarios over a 15-year timescale, designated as per a principal component analysis of the data discussed in the Section; (b) Fibonacci sequences of LES results, wherein the total pressure P_T keeps constant in the stream tube when the ventilation rate is not too small, by analogy to wind pressure P_W is decided by the position of the opening; (c) Projected cytometry of total pressure P_T' at the same opening position of a sealed room model is similar to the P_T at opening (ΔP is the tangential dynamic pressure, and the value is the difference between P_T and P_W) with significant Marks-Kendall metric, with scatter plots of Trellis-density correlations between studying the impact of varying wind direction on coefficient of variation (CV) in a wind tunnel by innovative utilization of a revolving turntable and wind direction fluctuations. was determined and modified by an on-site measurement using an ultrasonic anemometer in Shanghai; (d) Clockwise schematics of case studies incorporated for the machine learning analysis; (e) Polar Akima Interpolation of prevailing wind angle varied between $-45°$ and $+45°$ with 4 different fluctuating periods $(6, 9, 18$ and 36 s) in wind tunnel, rectified via Python t–SNE Dimensionality Reduction; (f) Normalized Laplace transform of the relationship between P_R^* and the discharge coefficient C_d inflow direction β.

Measurement principles

The COVID-19 pandemic has highlighted the essential role of fluid dynamics in the transmission of respiratory infections through various means including exhalation, speaking, singing, coughing, and sneezing [129]. It is vital to understand this interaction to effectively manage patient care facilities because many individuals with symptomatic COVID-19 may expel mucosalivary droplets into the environment [130]. Furthermore, medical procedures that generate aerosols, such as intubation, extubation, and oxygen delivery, can result in both surface and air contamination [131]. The MERS coronavirus is transmitted nosocomially, possibly from severely ill, long-term hospitalised patients [132]. Laboratory studies have shown that SARS-CoV-2 remains infectious for at least 3 h after aerosolisation and for up to 72 h on the surface. An environmental sampling study on SARS-CoV-2 discovered the virus in the air vents of a symptomatic patient's hospital room [133]. This finding indicates long-distance movement of viral particles, contradicting the large-droplet theory of viral transmission, which suggests that large droplets travel farthest, land on surfaces, and contaminate only those surfaces [134]. The detection of viral particles in air vents aligns with the multiphase turbulent gas cloud emission model [135]. This model posits that droplets become trapped within a gas cloud, enabling them to travel a considerable distance from the patient before being carried by ambient airflows at a slow speed of a few centimetres per second over the course of hours or even days [136]. Although it is difficult to definitively prove this hypothesis, especially during the ongoing pandemic, the precautionary principle outlined in the SARS Commission's 2007 report recommends that healthcare workers should be equipped with superior personal protective equipment, specifically N95 respirators, which were in short supply during the initial stages of the pandemic in the Western hemisphere [137]. It is worth questioning whether the distribution system of personal strategies was at the beginning of the epidemic rather than scientific evidence and the precautionary principle [138]. Insights into disease transmission, the effectiveness of masks and new materials for source control, and the reduction of contaminants from protective equipment can be gained through the application of fluid dynamics [139]. The factors to consider include the safety of medical procedures, such as aerosol-generating procedures or routine patient care in field hospitals during a pandemic, hand washing, social distancing requirements affecting occupancy number and duration in different environments, decontamination innovations, indoor air hygiene strategies facilitated by ventilation types, air filtration, decontamination, conditioning systems, and localised flow control solutions [140]. Flow heterogeneity plays a crucial role in the spread of indoor infections [141].

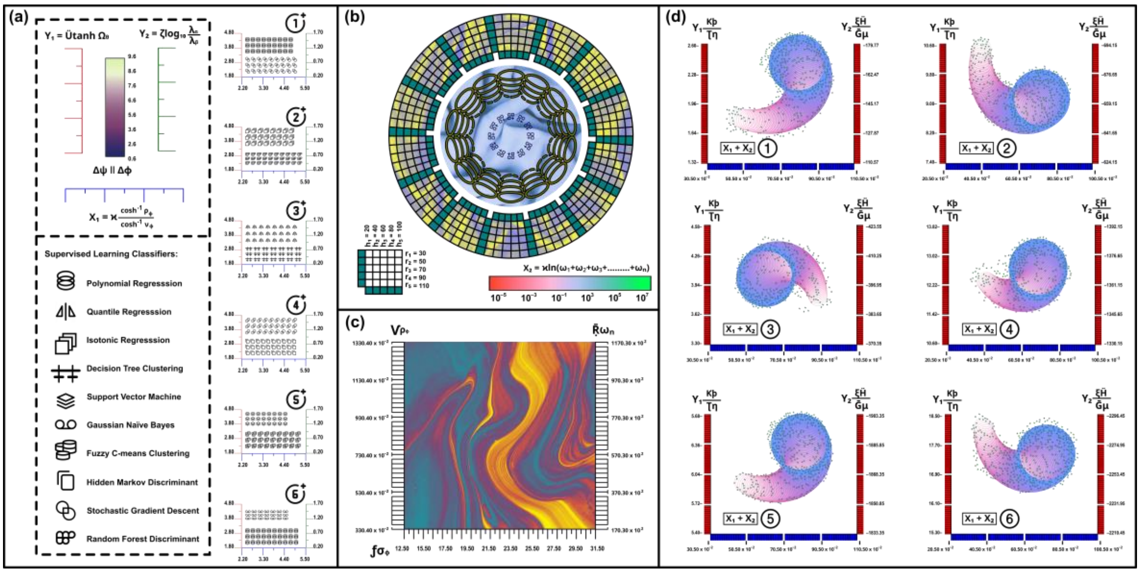

Figure 2 (a) Stacked hierarchical band structure (simulated in 6-sets via nominal range sensitivity analysis) of supervised learning classifiers within the Trellis-density correlations, clustered by double Y-axes' offsets in standard XY scale; (b) Sankey-visualization of stacked histogram plots depicting a normal distribution of the connection between discharge coefficient and P_R^* the opening is located at the windward side, which experimentally validated the Local dynamic similarity model; (c) Schoeller-Contour profile of $k - \varepsilon$ two-equation turbulence models (i.e., the RNG $k - \varepsilon$ framework involving indoor airflow, double skin façade and solar chimney), depicted alongside a spectroscopic packing of Bland-Altman density data; (d) Stochastic cylindrical resonances highlighting the covariance of changes in façade temperatures with (i) absorptivity (α_{IR}) ranging between $0.1 - 0.25$, the temperature of inner façade's changed from $41.2\ ^{\circ}\mathrm{C}$ to $49.4\ ^{\circ}\mathrm{C}$, and (ii) the reflectivity (ρ_{IR}) ranging between $0.07 - 0.3$, the inner façades' temperature lying within $38.2 - 43.7\ ^{\circ}\mathrm{C}$, arranged based on the offsets of two Y-axes in a conventional XY scale.

Remediating airflow heterogeneities is crucial, because

The well-mixed limit of indoor ventilation represents the greatest pathogen dilution limit, offering a minimum exposure risk in an indoor setting [142]. It is known that this limit needs to be adjusted owing to changes in indoor environments, such as variations in buoyancy sources (occupants and equipment) and fluctuations in venting caused by natural movements (oscillations and door and window openings) [143]. These factors can lead to the accumulation of contaminants in specific areas [144]. will likely provide more knowledge on how to enhance non-pharmacological interventions and mitigation strategies to fight the spread of COVID-19 [145]. Governments worldwide are progressively relaxing lockdown measures and aiming to bolster their capacity to manage anticipated waves of the pandemic by adopting a comprehensive approach that involves managing people, air, surfaces, and space [146]. This involves the implementation of practices such as hand hygiene, cleaning, limiting occupancy, managing indoor spaces and air quality, and utilising suitable protective equipment, such as specific types of masks, based on the situation or activity [147]. Pathogens transferred by fluids and droplets can spread via means other than the respiratory route [148]. Approximately 23 million infections and 50,000 hospitalisations in the United States each year are attributed to norovirus [149]. Clostridium difficile is a major cause of gastroenteritis-related mortality, causing almost 500,000 infections and approximately 29,000 deaths in the United States in 2011, with annual costs exceeding US$ 1.1 billion annually [150]. Clostridium difficile mortality rates are comparable to those of ovarian, brain, or kidney malignancies, and between December 2013 and September 2014, the Ebola virus disease outbreak in West Africa resulted in over 2,000 fatalities [151]. These disorders commonly present with signs of diarrhoea and vomiting [152].

Table 3 Estimated removal efficiencies for various mitigation techniques.

Strategy	Masks	Outdoor air	PAC	MERV filter	In-Room GUV	In-Duct GUV
Removal efficiency (%)	M	$\frac{Q_{oa}C}{G}$	$\frac{\eta_{ac}Q_{ac}C}{G}$	$\frac{\eta_{MERV}Q_{rec}C}{G}$	$\frac{Q_{UVr}C}{G}$	$\frac{(1-\eta_{MERV})\eta_{UVd}Q_{rec}C}{G}$

As shown in **Tables 4** and **5**, recent research indicates that these emissions may include large concentrations of SARS-CoV-2, which are found in significant amounts on the surfaces of patient bathrooms [153]. Spills from surfaces, sinks, or toilet flushes in hospitals and other interior environments are frequently overlooked as potential transmission pathways. However, to date, only basic attempts have been made to measure their impacts [154]. Shared toilets in medical institutions are used by potentially sick patients, making them a probable source of indoor cross contamination [155]. This study aimed to investigate the potential of toilet flushes for pathogen transmission [156]. The research involved contaminating toilets with germ and then collecting samples from the surfaces and air following flushing [157]. Despite numerous flushes, this study found that not all organisms in the bowl were completely removed [158]. Furthermore, it was discovered that the droplets created during flushing contained organisms used for seeding, which remained airborne and viable [159]. In 2013, another study evaluated different toilet designs and found that each flush could release up to 145,000 particles from collected samples [160]. In public venues in North America, particularly in patient care settings, toilets often lack lids to minimise surface contamination from biofilms or superbugs [161].

However, systematic studies on the source conditions and fluid dynamics of pathogen emissions in bathroom settings, such as flushes and water splashes from hand washing, are currently lacking [162]. Researching the fluid dynamics of fragmentation and aerosolisation can aid in comprehending the emission dynamics and spatiotemporal progression of the spray and fragmentation processes [163]. **Figure 2(c)** depicts a toilet flush recorded at 2,000 fps in the recent direct visualisations conducted by [164]. To mitigate droplet collection on surfaces, adhere to the surface cleaning measures outlined in local infection control guidelines [165]. No existing systems or practices address air pollution [166]. It is also important to scrutinise the mechanics of bubbles and their role in the generation of secondary contaminated droplets [167]. Other fragmentation mechanisms were examined in [168].

Experimental frameworks

Previous sections have demonstrated that fundamental physics, particularly interfacial and fragmentation dynamics, can explain the various mechanisms related to disease dispersion and transmission [169]. Organisms have evolved to control these processes and to spread and multiply [170]. This section focuses on the interaction between the bubbles at the bulk fluid interface [171]. Bubbles are commonly found on the surface of water and can pose public health risks by producing droplets that may contain infectious agents, thereby facilitating the spread of airborne diseases [172]. These droplets can be easily carried over short and long distances by drafts and the wind [173]. The transmission of infectious diseases by inhalation of droplets or droplet nuclei harbouring germ cells is well-established in both human and animal populations. Therefore, when a bubble ruptures, it expels droplets [174]. Thinner bubbles, which are usually older, release a greater number of smaller and quicker droplets than broader bubbles, which are usually younger [175]. Additionally, thinner films experience higher acceleration when the cap is opened, causing a more intense destabilisation of the developing rim owing to Rayleigh-Taylor instability [176]. Microorganism-contaminated bubbles remain on the bubble cap for the entire duration of the bubble existence [177]. Older bubbles can release several contaminated droplets when they break [178]. Bubbles near the surfaces of distilled, bottled, or pure tap water burst rapidly [179]. During their brief existence at the interface, the thickness of the bubbles is altered by the interaction with the surrounding air in a surprising and paradoxical manner: cooling the upper part of a bubble reduces its surface tension and enhances evaporation compared to the lower part, which remains at ambient temperature [180]. This difference in surface tension causes water to move from an area of low surface tension to an area of high surface tension owing to the thermal Marangoni flow [179]. This upward movement counteracts the draining of the bubble film, resulting in older and thicker clean bubbles [181]. The replenishing effect of evaporation is universal and can be caused by temperature variations between the main fluid and the top of the bubble cap owing to evaporative cooling, as well as gradients of chemical or biological compounds [182]. Additionally, volatile chemicals such as alcohols and salts can exacerbate this phenomenon [183]. Bacteria produce secretions that stabilise bubbles, making them resistant to disruptions that would typically cause clean bubbles to burst quickly [184]. The secretions produced by bacteria have properties similar to those of surfactants, which allows them to extend the lifespan of soap bubbles [185]. Thicker caps are often more resistant to external disturbances, resulting in bubbles that can last longer [186]. Surface-active chemicals can enhance the interface, leading to increased elasticity and an extended bubble lifespan [187].

Understanding how this change in regime affects the transmission of pathogens from water to air is crucial for determining the effectiveness of infected bubbles with lifespans exceeding 10 - 20 s in producing contaminated droplets [188]. The interplay between water evaporation and Marangoni flow results in a change in the thinning law, which affects pathogen transmission [189]. Bacterial secretions can affect bubbles, even in bacteria such as Escherichia coli, which are not commonly associated with biofilm production [190]. Marzouk *et al.* [191] demonstrated that bacteria can influence the interfacial physics within contaminated bubbles to enhance long-distance dissemination. It is essential to recognise that infections should not be considered passively conveyed in fluids without influencing the physical processes of the medium transporting them, even though they may have a small size, low concentration, and minimal impact on the static surface tension of the fluid [192].

Table 4 Data points required to run the CONTAM-quanta model of the first-floor core zone of the DOE large-office prototype.

Inputs	Parameters	Type	Magnitude	Data source
Zone geometry	Volume $(m^3)/Area\ (m^2)$	Core	6,376/2,324	[47]
		Perimeter West (Perimeter East)	608/224.5	[49]
		Perimeter North (Perimeter South)	803/288	[55]
		Restroom	277/100	[58]
		Stairs (Elevator Shaft)	75.7/27.6	[68]
		Data Center	98.6/36.0	[72]
Zone occupancy	Infector	-	1	[61]
	Susceptibles		133	
Initial quanta concentration	Concentration (quanta/m³)	-	0	-
Quanta generation	Quanta generation rate (quanta/h)	-	65	[24]
	Breathing rate (m^3/h)		0.72	[36]
	Generation duration		$8:00-17:00$ (9 h)	[112]
Deposition and deactivation	Surface deposition rate	-	$0.3\ h^{-1}$	[37,48]
	Viral particle deactivation rate		$0.63\ h^{-1}$	[79]
Germicidal	in–room GUV removal rate	-	$4\ h^{-1}$	[51]
Ultraviolet light	in–duct GUV removal efficiency		87 %	[79]
	MERV8 removal efficiency		20 %	[59]
MERV removal	MERV11 removal efficiency	-	65 %	[33]
	MERV13 removal efficiency		85 %	[114]
PAC airflow rates	PAC1	-	$0.46\ m^3/s$ (975 CFM)	[117]
	PAC2		$1\ m^3/s$ (2,140 CFM)	[121]
	PAC3		$1.45\ m^3/s$ (3,075 CFM)	[124]
	PAC4		$17\ m^3/s$ (36,000 CFM)	[126]
	HEPA removal efficiency	-	99 %	[130]
Mask	Mask wearing percentage		0 or 100 %	[133]
	Exhale removal efficiency		50 %	[137]
	Inhale removal efficiency		30 %	[141]

Tools and techniques

Crop diseases can have a significant impact on yield as well as historical consequences, as evidenced by the Irish potato famine of 1845, which resulted in the displacement of millions of people and approximately one million fatalities owing to the spread of Phytophthora infestans [193]. An estimated 10 % of global crops are lost each year to plant diseases, resulting in billions of dollars in projected costs, particularly in areas with limited resources [194]. Plant diseases can spread over long distances through established meteorological patterns or exceptional events such as hurricanes [195]. Erosion and surface runoff can also contribute to the movement of soil and landscapes. The focus was on the transmission of rainfall-induced diseases on a host-to-host scale, as the physics of long-distance dispersion and erosion have been addressed in other studies [196]. Spores and bacteria trapped in sticky mucilage can only spread through contact with the liquid phase, and rainfall often triggers foliar disease outbreaks [197]. Lesions on crops typically appear a few weeks after rain events, with new lesions emerging at the base of wheat leaves after rainfall and preceding epidemics of other plant diseases, such as Septoria tritici, Septoria nodorum, yellow rust, and tan spot [198]. In laboratory experiments, simulated rainfall contaminated the area surrounding an infected plant [199]. As shown in **Tables 4** and **5**, further research is needed to develop physical models of rain/irrigation-leaf interactions to better understand the mechanisms that influence pathogen distribution and provide universal methods for various canopies and rain intensities [200]. This research can also aid in improving the disinfection of vegetables after harvest [201]. Modelling the spread of foliar diseases requires an understanding of the physical mechanisms that influence pathogen distribution, which is essential for monitoring, predicting, and controlling outbreaks [202]. An improved understanding and modelling of the complex spray physics and interactions between sprays and crops are essential for optimising the timing and quantity of applied chemicals and minimising losses due to spray drift [203]. Current research on the spread of diseases through rain splashes has primarily relied on statistical simulations that utilise empirical methods without fully resolving the underlying physical processes [204]. The distribution of pathogens via the raindrop effect on contaminated leaves involves interplay between the fluid dynamics of the raindrop, biophysical characteristics of the pathogen, and biomechanical properties of the leaf [205]. The rapid local movement of droplets as they impact leaves is influenced by various morphological and mechanical traits that determine the spread of contamination around plants [206]. Surface features such as roughness, venation pattern, and wetting properties of leaves play a critical role in defining local transmission dynamics. The wetting properties of leaves determine whether they are covered in droplets or films after rainfall, irrigation, or dew [207].

Table 5 Comparison of CONTAM (FaTIMA)-quanta single-zone and COVID-19 Aerosol Transmission Estimator.

Zone volume	**CONTAM (FaTIMA)-quanta**		**COVID-19 aerosol transmission estimator**	
	810 m^3	**Value**	**810 m^3**	**Value**
Generation	Number of infectors	1	Number of infectors	1
	Particles/Quanta generation rate	970 quanta/h	Infective person	970 quanta/h
Removal	Supply air rate	567 m^3/h	Ventilation with outside air	0.7 h^{-1}
	Return air rate	567 m^3/h (0.7 h^{-1})	-	
	Exhaust air	567 m^3/h (0.7 h^{-1})	Exhaust air	567 m^3/h (0.7 h^{-1})
	Air cleaner (Filter)	0	Additional control measures	0
	Surface deposition	0.3 h^{-1}	Surface deposition	0.3 h^{-1}
	Inactivation of the virus	0.63 h^{-1}	Inactivation of the virus	0.63 h^{-1}

Previous research on rain-induced contamination dispersal has concentrated on 2 extreme cases: Superhydrophobic surfaces with very low wetting properties, and surfaces with very high wetting properties that result in a film coating on leaves [208]. However, new research has established a framework based on wetting and mechanical foliar qualities that has transitioned from a physical model of crown-vertical sheet fragmentation dynamics to 2 main forms of contaminated fluid emissions [209]. Inertial detachment can increase the distance that larger contaminated droplets travel, owing to a new disintegration and ejection process [210]. This is important because large ejected droplets are believed to increase the likelihood of infecting a healthy leaf by depositing a higher concentration of the pathogen in a confined area [211]. Increasing leaf flexibility initially appears to reduce the distance that disease-carrying droplets are expelled from the infected plant. However, this decrease in transmission efficiency in terms of range is offset by the inertial detachment fragmentation mode, which results in a high compliance [212]. This mode increases the risk of successful infection, owing to the larger drop size and higher potential pathogen load caused by reduced dilution upon fragmentation for inertial detachment fragmentation [213]. The boundary layer flow is influenced by the density, shape, and arrangement of plants, and the canopy can help improve the accuracy of the contamination range and distribution patterns. The significance of this method lies in its inability to specifically protect against a suspected pathogen; however, it can reduce the spread of a range of rain-or irrigation-induced illnesses in a particular area and facilitate effective intercrop spacing [214]. The knowledge gained is also applicable to broader processes of fluid and pathogen accumulation, dispersal, or elimination (such as contamination of produce by human or plant pathogens during irrigation) [215]. The intricate leaf shape in these applications causes the liquid sheet to break up in a non-symmetrical manner in air, leading to different distributions of drop sizes and speeds compared to symmetrical sheet fragmentation [216]. Various types of splashes occur when a crown strikes a thin film, deep pool, or near-surface margin, including unstable sheet development and breakup [217]. When the Weber number exceeded a specific threshold, the impact changed the drop volume into a spreading sheet with varying velocities and thicknesses [218]. This sheet is surrounded by a moving ring of varying thickness that breaks into droplets [219], thereby enabling a phenomenon called 'Respiratory fluid fragmentation' [220]. A similar progression from sheets to rims to drops was observed in [221]. To address the challenges associated with the emission and transport of pathogens in various populations and disease systems, it is crucial to accurately quantify and predict a simplified canonical unsteady fragmentation process owing to its universal nature [222]. The dynamics of classical unsteady sheet fragmentation occur when a drop impacts a target of similar size, as discussed in [223].

Sampling procedures

Case A: Human passage through an air curtain separating 2 corridor sections transports contaminants

Engineering specifications and calculations

The transfer of heat and movement of particulate substances through an open doorway owing to temperature differences between the 2 zones can lead to negative consequences in settings such as industrial manufacturing processes, laboratories, and hospital clean rooms [224]. To mitigate these issues, air curtains are commonly used to reduce buoyancy-driven exchange flows and limit the spread of unwanted substances [225]. One advantage of using an air curtain instead of mechanical structures, such as vestibules, sliding doors, or strip curtains, is that it enables unobstructed movement of both human and vehicular traffic through the entryway [226]. However, the interaction between an air curtain and a moving object, such as a person passing through a doorway, is not fully understood [227]. When a moving object passes through a doorway, it creates a wake that carries and mixes the surrounding fluid, aiding the movement of contaminants [228]. In certain studies, scenarios have been investigated in which a person moves through a doorway connecting 2 sections of a hallway with the same temperature and density, thus carrying pollutants across the 2 zones [229]. To minimise the second part of the study, we explored a scenario in which there is a density difference across the doorway, resulting in a buoyancy-driven exchange flow, where a human passes through an air curtain consisting of a downward-directed planar air jet produced by a centrifugal fan situated in a manifold above the doorway [230].

The basic setup of an air curtain is well understood; however, its use as an air curtain is currently being researched owing to the added complexity of wall impingement and the varying densities on each side of the jet [231]. The minimal momentum required for the air curtain to reach the other side of the doorway with and without wind was calculated by Sirén, who studied the thermal properties of the air curtain by developing an equation for thermal loss and comparing it with real-world data [232]. Numerical simulations, semi-analytical models, and laboratory-scale investigations in water align well with full-scale tests conducted on an air curtain within a completely sealed structure [233]. Frank and Linden researched how adding another ventilation route, such as an open window, impacted the efficiency of an air curtain, as well as how the air curtain's performance changed due to the shift in the neutral level [234]. They also studied a heated air curtain and found that the opposing buoyancy force decreased its stability, efficacy, and energy efficiency [235]. Wind and pressurised chambers can externally influence the air curtain, potentially leading to significant oscillations [236]. This study investigated the interaction between the wake of a moving person and an air curtain placed on a doorway, separating 2 zones with varying densities [237]. To achieve this, laboratory water-bath experiments were conducted to examine how a moving human, represented by a cylinder, interacts with an air curtain that divides 2 zones with different densities in a hallway [238]. The results derived from this review article thus outline how the current study might aid in improving the design of air curtains and explore techniques for minimising the impact of traffic on the efficacy of air curtains in real-world scenarios.

Key observations

Figure 1(a) presents a comprehensive explanation of the experimental measurements and techniques employed. The cylinder was moved to-and-fro between 2 fixed positions located at the midpoints of both sides, traversing from the saltwater side to the freshwater side and back of the tank. This scenario mimics an individual moving between a warm building and cold outdoor environment using a warm air curtain. Once the ACD on the freshwater side was activated, the jet flow stabilised, water levels on both sides were balanced, and the vertical gate was opened. The blue dye injection port for monitoring the air curtain was activated, thereby initiating the time measurement. The experiment for the other series concluded when the cylinder reached the middle of the opposite side after passing through the air barrier. Next, the vertical gate was closed and both the air curtain and dye ports were turned off. attributed this phenomenon to the fact that, although the moving cylinder disrupts the air curtain, the area behind the cylinder remains a turbulent flow field. The turbulence in the cylinder wake is anticipated to hinder and disrupt the directed buoyancy-driven stream, similar to how the air curtain impedes buoyancy-driven flow when there is no moving cylinder. found that the efficiency of an air curtain should be determined by buoyancy-driven exchange flow.

Sensitivity analysis

The current scenario of a doorway in a hallway resembles doorways between larger rooms, suggesting that the interaction at the doorway is not affected by room layouts and is instead determined locally at the doorway. When functioning optimally, the air curtain remained stable and touched the floor, focusing solely on the situation in which the air curtain continually made contact with the base of the tank without interruption. Raines *et al.* [239] displayed dye visualisations and analysed them to enhance the understanding of flow and efficacy measures. Flow visualisation was performed for 3 distinct cylinder speeds and 4 varying deflection modulus values. The infiltration flux did not appear to be influenced by the direction of movement. Therefore, only the findings for the cylinder moved from the dense to the lightfluid side of the tank. shows side views of the cylinder travelling from left to right, as indicated by the arrow. When the cylinder neared the air curtain, the air curtain shifted slightly in the direction of movement of the cylinder. The main disturbance occurs when the cylinder is behind the air curtain. Following the passage of the cylinder through the air curtain, the dense red fluid infiltrated the light-fluid side, as the curtain was re-established. The air curtain was reestablished at a later period by piercing the wake.

Deterministic prototypes

Figures 1(a) - **1(c)** highlights the moment when the air curtain was initially restored, while **Figures 1 (c)** - **1(e)** shows the plan views of the interaction for identical parameter values. As previously stated in the introductory portions of this section, the cylinder had a base with a larger diameter that obstructed the view immediately next to it. The wake width widened as the distance from the cylinder increased, causing the spanwise breadth of the infiltration to increase over time. The air curtain is re-established in this scenario after the cylinder has moved by approximately five-cylinder diameters, as shown in **Figures 1(d)** - **1(f)**, and depicts the interruption and restoration of the air barrier at various cylinder speeds and deflection moduli. The images captured the intrusion when the curtain was initially reinforced. For Particle Image Velocimetry (PIV), the movement of the curtain front was monitored at 100 fps, selecting every fourth frame from the PIV recordings. In contrast, front tracking for dye visualisation was conducted at 24 fps, and the noticeable peak in the recorded curve during the PIV experiment was due to the presence of a powerful eddy near the leading edge of the curtain. Furthermore, it closely resembles dye tracking utilising buoyancy. The longer it takes for the air curtain to re-establish at higher cylinder speeds, the less effective it becomes, as indicated by measurements. Thus, the findings suggest that there is no notable nonlinear relationship between wake and gravity streams. Ramirez-Mata *et al.* [240] conducted research on a cylindrical object that represents a human moving through an air barrier separating 2 areas with different densities or temperatures in a hallway, and found consistent outcomes regardless of the cylinder's direction of travel, whether it was moving from the dense fluid side to the light fluid side or vice versa. Razavi *et al.*

[241] discovered that entrainment in the cylinder wake increases at a higher cylinder speed owing to the higher wake velocity, leading to a longer period for the re-establishment of the curtain. Rezaeieh *et al.* [242] showed that dimensionless numbers were comparable to those observed in real-scale processes. Recent investigations have revealed that human and vehicular traffic decreases the effectiveness of air curtains [243]. To reduce the disruption of the air curtain, we recommend slowing down the traffic before it reaches the air curtain and crossing it at a significantly lower speed. These results are consistent with these recommendations [244]. **Figures 2(a) - 2(c)** illustrates the curtain re-establishment characteristics at various cylinder speeds, and lines were used to display the data patterns and differentiate between different settings [245]. This air curtain can be used as a doorframe between 2 rooms or between a room and an open outside, as is commonly observed in real-life situations [246].

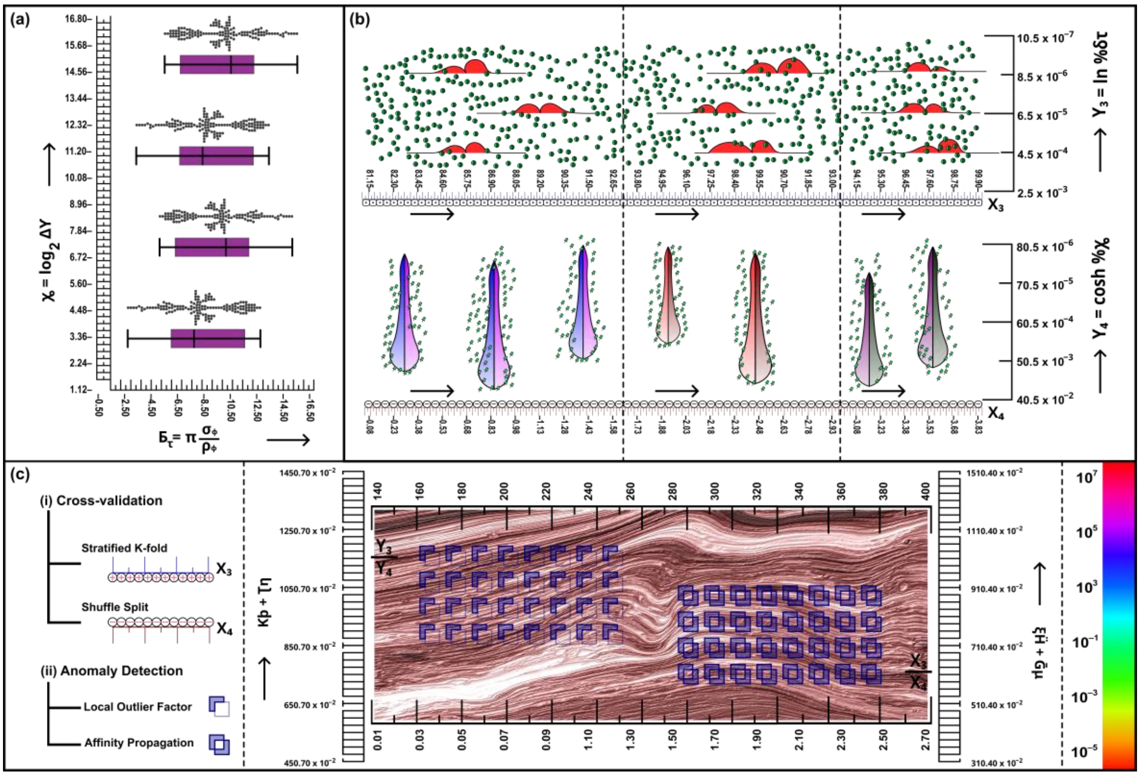

Figure 3 (a) Simulation results of the RNG $k-\varepsilon$ framework (with enhanced wall function for first layers $y+<1$, that delivered good agreement between CFD and experimental results) expressed as Notched box-chart with outliers; (b) Verification of experimental results with direct absorption ($\tau_1 \cdot \alpha_2 \cdot I_{solar}$), (wherein the influence of low-e coating's reflectivity on the outer façade is determined by the secondary reflection ($\tau_1 . \rho_2 \cdot \alpha_1 \cdot I_{sola}$).illustrated as raincloud and grouped-violin plots; (c) Posthoc verification of the data plots pertaining to ventilation rate (that performs almost in a power function correlation over the value of $\cos\theta: V = 0.041(\cos\theta)^{0.31}$ ($R^2 = 0.9983$) for NVDSF I; and $V = 0.047(\cos\theta)^{0.31}(R^2 = 0.9971)$ for NVDSF II, where V is the volume flow rate (m^3/s) and θ is the incident angle), illustrated as cross-validation and anomaly detection.

Case B: Control of exhaled SARS-CoV-2-laden aerosols in a ventilated room with limited space air stability

Engineering specifications and calculations

The escalating global concern arises from the human-to-human transmission of Severe Acute Respiratory Syndrome Coronavirus2 (SARS-CoV-2) during the COVID-19 pandemic, which underscores the importance of readying effective control measures in advance for the re-emergence of SARS-CoV-2 or other potential pandemic risks such as COVID-19 [247]. Individuals are requested to maintain social distancing and self-isolation at home to limit the transmission of COVID-19 [248]. Individuals who are infected and experience moderate symptoms are instructed to self-quarantine in their own homes, which may lead to a higher likelihood of a second SARS-CoV-2 outbreak among family members as they have a greater risk of COVID-19 infection than other demographic groups [249]. Individuals who are undiagnosed or asymptomatic may be in close proximity to others in a room without taking protective steps, possibly exacerbating the problem. Confined areas such as cabins, cruises, and hospital wards have been identified as high-risk environments for SARS-CoV-2 transmission, highlighting the significance of utilising engineering and environmental strategies to regulate the spread of airborne SARS-CoV-2 aerosols and mitigate the risks of infectious diseases in confined spaces [250]. A known method for SARS-CoV2 transmission is airborne respiratory aerosols containing viruses released during respiratory actions, such as breathing, coughing, and sneezing [251]. Aerosols that can be carried and remain suspended in the breathing zone by exhaled air are influenced by factors such as the aerosol size, airflow patterns, and indoor temperature distribution [252]. These factors affect the path of exhaled infectious SARS-CoV-2-laden aerosols in the breathing zone [253]. Based on the Reynolds analogy and extended Reynolds analogy, the heat and mass transfer mechanisms and shear stress in incompressible flows exhibit similar traits, suggesting that the gas transport process is linked to the particle transport process in an exhalation flow [254]. Traditional airborne aerosols containing SARS-CoV-2 have been used for research on COVID-19 transmission [255]. Traditional ventilation systems may not always be as effective as expected in lowering the risk of airborne cross-infection in certain situations [256]. Displacement ventilation can cause heat layering in the space, potentially trapping inhaled contaminants near the breathing height and increasing the risk of infection in individuals in close proximity [257]. Augmenting the ventilation rate can help decrease the spread of airborne infections [258]. However, higher ventilation rates often result in increased energy consumption during mechanical ventilation [259]. Advanced solutions, such as integrating ventilation systems with other engineering and environmental control systems, should be devised to manage the spread of COVID-19 and reduce the chances of cross-infection [260].

Air stability in confined spaces has recently become a topic of interest [261]. In 2010, the categorisation of air conditioning in confined spaces was dependent on the vertical temperature distribution, which could be classified as stable, neutral, or unstable [262]. The level of contaminants in exhaled breath varies based on the stability of air in confined spaces, as reported by [263]. Under stable conditions, contaminants are confined near the release height and dispersed along the initially released direction, whereas under unstable conditions, contaminants tend to disperse quickly from their original locations [263]. Recent research has shown that an unstable state can significantly decrease the number of contaminants in the air surrounding an individual in a ventilated space [264]. However, the impact of combining ventilation strategies and restricted space air stability on regulating the transmission of airborne SARS-CoV-2 aerosols and reducing the risk of COVID-19 infection in the respiratory microenvironment among individuals remains unclear [265]. To address this, a sophisticated engineering and environmental control system was introduced that combines limited space air stability conditions with a ventilation system in a room [266]. This study examined how this system affects the spread of airborne SARS-CoV-2 aerosols in the breathing microenvironment of 2 individuals using experimental and numerical analyses [267]. Two human volunteers participated in the study, performing the standard breathing technique of inhalation through the nose and exhalation through the mouth [268]. A numerical model was created using experimental parameters to represent the flow field visually [269]. The simulation results were used to analyse how the ventilation rate affects the distribution of temperature and aerosol concentration [270]. These results can enhance our understanding of how inhaled airborne SARS-CoV-2 aerosols are transmitted between individuals in close proximity [271].

Key observations

A few studies have examined test rooms featuring individuals adopting a specific breathing style and positioning, which poses the highest risk of exposure [272]. The engineering and environmental control system in the test room was established by implementing 3 distinct air stability conditions: Stable, neutral, and unstable situations in a total-volume-ventilated test room with a bottom supply and top exhaust. These conditions were achieved by regulating the temperature of the radiant air-conditioning system situated above the ceiling and the electric blankets positioned on the floor, which were divided into 2 segments. During the first half, known as Part A, a 30-minute tracer gas was released, while 2 test volunteers engaged in breathing activities. A wire anemometer is used to measure the flow rate of the ventilation system. Numerical simulations were performed using the CFD approach to provide a clear visual representation of actual physical events. A hybrid mesh approach is used to mesh the geometric model. The computing domain was divided into zones comprising the CSPs and the rest of the room. The occupied region is separated into unstructured tetrahedral cells, whereas the remaining space is divided into structured hexahedral cells. The boundary between the occupied area and surrounding region was addressed using an appropriate technique. This hybrid approach ensures a high-quality mesh. Grid independence was assessed using 3 different grid resolutions: 1,937,399 (Grid 1), 2,324,634 (Grid 2), and 5,551,878 (Grid 3). The study utilised the SIMPLEC velocity-pressure coupling technique and second-order upwind spatial discretisation approach for both steady and transient calculations. The transient calculations commenced with a completely converged steady state outcome. Two reference examples (examples 7 and 8) were simulated without restricted space air stability circumstances, using the floor and ceiling as adiabatic walls. This was done to compare them with the numerical results of Cases 1 - 6 and to emphasise the impact of limited space air stability conditions.

Sensitivity analysis

The level of concentration in the breathing microenvironment is determined by the flow of breath and overall airflow in space. This factor varies among test subjects [273]. Previous research has shown that stable stratified air can trap exhaled pollutants at a specific height in a breathing environment, leading to increased exposure hazards [274]. In this study, the same phenomenon was observed when the ventilation system was set to a steady state, which resulted in the creation of an air environment with stable stratification. Despite the high velocity of the supplied air causing turbulent mixing in the room, the concentration measured in the stable case was higher than those in the neutral and unstable cases. This suggests that the mixing effect of ventilation rate may be offset by the confinement effect of stable conditions, leading to the accumulation of SARS-CoV-2-laden aerosols in the breathing microenvironment. Overall, this study indicates that the effectiveness of a ventilation system in eradicating inhaled SARS-CoV-2-laden aerosols from the surrounding air depends on the air stability conditions in confined spaces. The concentration distribution at different heights was generally lower for the unstable and neutral conditions than for the stable case, regardless of the presence or absence of test subjects. As previously noted, inhaled SARS-CoV-2-laden aerosols were more abundant in the stable case but dispersed better in neutral or unstable cases.

Figures 2(b) - 2(d) show a comparison between the temperature profiles of the experiment and Computational Fluid Dynamics (CFD) findings for stable, neutral, and unstable scenarios. The numerical findings were in agreement with the experimental results. An existing numerical model was used to calculate the flow field in the breathing microenvironment. **Figure 3(a)** shows the temperature profiles for stable, neutral, unstable, and reference scenarios. The temperature distribution in the room exhibited stratification, which is a common characteristic of displacement ventilation [275]. Research has shown that layering can provide a trapping effect on exhaled pollutants in a small breathing environment [276]. Singh *et al.* [277] also revealed that dual-layer temperature stratification emerges under neutral conditions (as depicted in **Figure 3 (b)**). This indicates that the neutral state was more responsive to increased ventilation rates than the conventional ventilation systems without supplementary features. Under steady conditions, an improved temperature stratification was observed, as shown in **Figure 3(c)**. However, the significant temperature contrast could trap inhaled aerosols, posing a higher risk of infection to those in the vicinity. While increasing the ventilation rate resulted in increased turbulence within the room, a stratified temperature distribution was maintained to guarantee a stable air environment, as illustrated in **Figure 4(a)**. Prior hypotheses were corroborated in that the mixing effects of higher ventilation rates were partially offset by the confinement effect of stable conditions.

In essence, the stratified flow pattern in stable environments is less likely to be perturbed by increased ventilation rates compared with other confined space air stability scenarios. This may not always reduce the risk of COVID-19 cross-infection in confined spaces with stable conditions, as exhaled aerosols containing SARS-CoV-2 may still be confined within the breathing microenvironment owing to the stable stratification of air. **Figure 4(b)** shows more mixed air environments when analysing the unstable ventilation system compared to the pure displacement ventilation situations depicted in **Figure 4(c)**. The cooled ceiling and heated floor generated strong convection and increased air entrainment. The ventilation rate did not affect the difference in concentrations between the tracer gas and aerosol particles in 2017. The distribution of the tracer gas shown in **Figure 1(b)** indicates that a significant portion of the exhaled SARS-CoV-2-laden aerosols was concentrated in the upper breathing microenvironment. The expelled mainline from CSP A exhibited a tendency to divert upwards and cross over CSP B. In the steady-state scenario shown in **Figure 2(b)**, the exhalation flows were fully confined at the release height and moved horizontally towards each other. The 2 exhalation streams from CSP A and CSP B converged at the centre of the breathing environment, leading to the highest risk of infection, and the transmission of aerosols was restricted to a stable state. The enlarged contaminated area in the reference scenario is shown in **Figure 1(c)**, which demonstrates that the increased turbulent mixing resulting from the higher ventilation rate accelerated the spread of exhaled aerosols. The polluted area expanded in both the vertical and horizontal dimensions, covering the entire room in both neutral and unstable situations, as illustrated in **Figure 2(c)**. The contaminated region was larger than that in the reference case. Under stable conditions, the transport of exhaled aerosols was not influenced by changes in the breathing rate. The spread of aerosols containing SARS-CoV-2 remains suspended in the breathing zone with minimal movement outside the personal breathing space. The risk of infection was highest in this case. Although the neutral and unstable cases had larger polluted areas than the stable case, the accumulation of SARS-CoV-2-containing aerosols in the personal breathing microenvironment was lower.

Thus, this study revealed that the performance of a ventilation system in eradicating airborne SARS-CoV-2 particles in enclosed spaces is influenced by the stability of the air. In unstable and neutral settings, the concentration of SARS-CoV-2-laden aerosols in the respiratory microenvironment of a room with displacement ventilation is lower than that under stable conditions. It is important to assess ventilation methods that are appropriate for air stability. Rooms with in-floor heating and ceiling cooling systems often exhibit unstable and neutral conditions, respectively. To mitigate the risk of spreading SARS-CoV-2 infection through indoor air, the use of total-volume ventilation methods, such as mixing and displacement ventilation, is recommended. However, in situations involving ceiling heating or floor cooling, these methods may not be effective in removing infectious aerosols from the breathing area, posing a significant risk of infection to nearby people. Therefore, local ventilation techniques should be used in confined spaces to eliminate SARS-CoV-2-laden aerosols from the immediate breathing zones between individuals. Local ventilation systems, such as push and pull ventilation systems, are designed to remove pollutants and heat from occupied spaces. These systems rely on locally capturing impurities, and the exhaust opening should be positioned in the major direction of the predicted emissions, often on the rear wall. Additionally, the exhaust opening should be positioned on the windward side of the mainstream exhaled pollutants under steady conditions to efficiently eliminate exhaled SARS-CoV-2-laden aerosols from the breathing microenvironment. It is worth noting that local ventilation techniques are effective in removing pollutants and heat from the area but may not be sufficient to eliminate all SARS-CoV-2-laden aerosols. Therefore, other measures such as wearing masks and practising physical distancing should be implemented in conjunction with ventilation techniques to reduce the risk of infection.

Deterministic prototypes

This study conducted a comprehensive examination of the spread of SARS-CoV-2-containing aerosols in the immediate breathing zone, using both experimental and computational data. This study found that the movement of inhaled SARS-CoV-2-laden aerosols in a ventilated space was significantly influenced by air stability in a restricted area. The following conclusions were drawn from this research: 1. In a displacement-ventilated room, both neutral and unstable conditions were more effective in removing breathed SARS-CoV-2-laden aerosols from the air, regardless of the presence of test subjects. Neutral and unstable situations result in a greater dispersion of SARS-CoV-2-laden aerosols throughout the room compared with stable conditions; however, the concentration of exhaled aerosols in the interpersonal breathing microenvironment is lower. Neutral and unstable conditions may reduce the risk of infection among individuals living in confined spaces. The effectiveness of a ventilation system in removing infectious airborne SARS-CoV-2-laden aerosols from the immediate breathing area between people relies on the air stability conditions in confined spaces. The stable scenario demonstrated a more consistently stratified temperature field than the pure ventilation system, resulting in a flow pattern that was less susceptible to changes in the ventilation rate.

The use of increased ventilation rates has been found to effectively traps a significant portion of exhaled aerosols containing SARS-CoV-2 within the immediate breathing space between individuals, thereby increasing the risk of infection. A higher ventilation rate was more effective in reducing the concentration of SARS-CoV-2-laden aerosols than a conventional ventilation system, without additional features. The study found that both ventilation rates created a uniformly mixed-temperature environment, leading to the least polluted breathing space between individuals. Based on the assessment of air stability conditions in confined spaces, recommendations for appropriate air distribution methods are provided. It is suggested that total-volume ventilation methods are suitable for unstable and neutral conditions to reduce the concentration of SARS-CoV-2-laden aerosols. However, local ventilation methods are recommended for stable conditions to directly eliminate infectious SARS-CoV-2-laden aerosols from the immediate breathing environment. The findings of this study will be useful in providing practical guidance for managing the spread of infectious SARS-CoV-2-laden aerosols and minimising the risk of COVID-19.

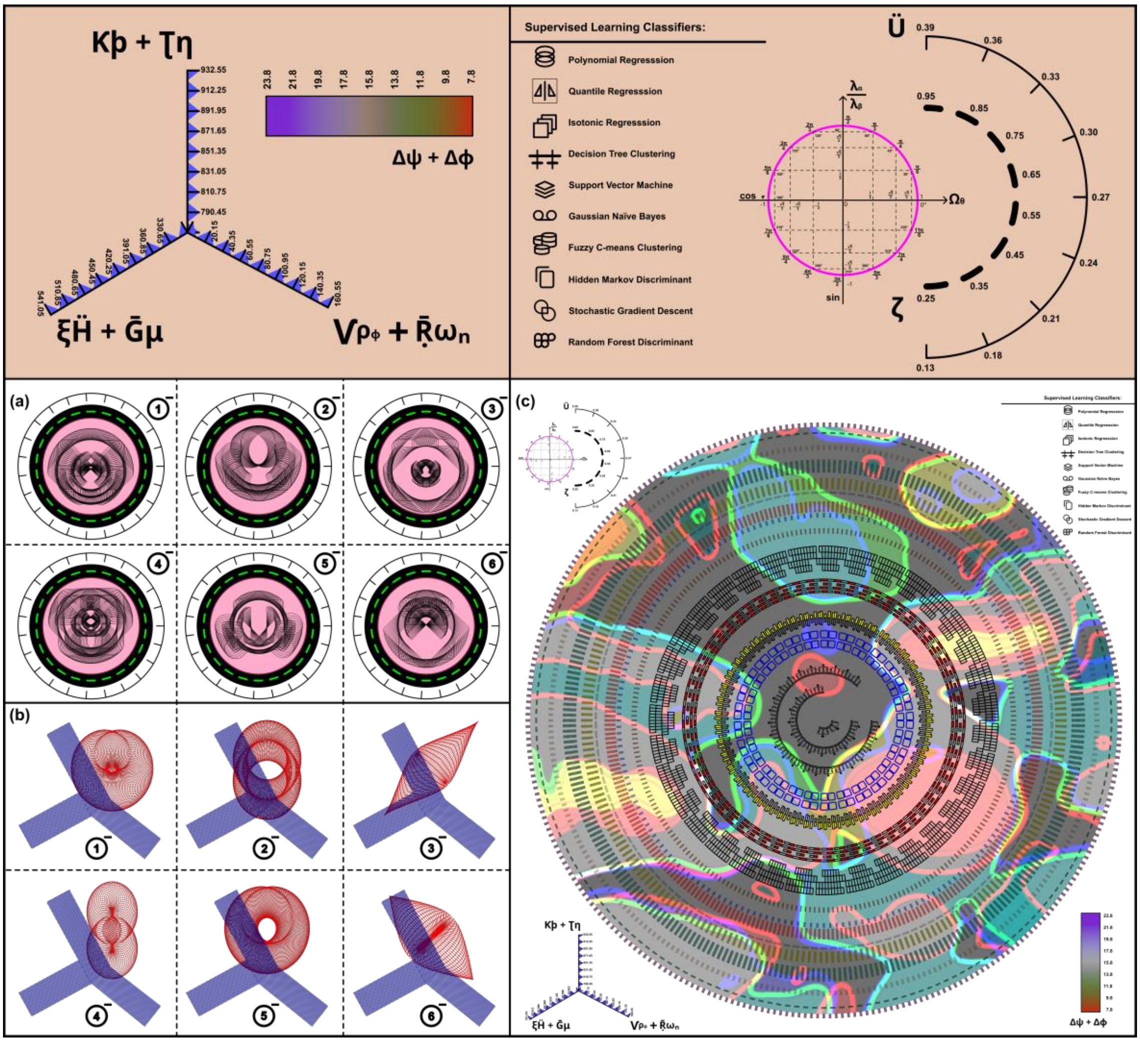

Figure 4 (a) Angular response-surface plots of natural convection (that improves over a higher absorptivity percentage, though the change is less significant when compared to a fixed reflectivity, wherein ρ_i reduces over higher α_i) and highest reflectivity ($(\alpha_i/(\alpha_i + \rho_i) = 42\ \%$), wherein the greatest exterior glass temperature is 52.0 °C and the lowest inner glass temperature is 52.7 °C (as the fraction of α grows, the façades can achieve a greater inner temperature of 54.5 °C, but a lower outer façade 50.8 ˚C) nexus estimated via the 6-set hierarchical bands of machine-learning classifiers; (b) Corresponding stochastic response spectra of the relationship between flow rates and solar intensities for NVDSF I and II (i.e., $V = 0.0039I^{0.33}, (R^2 = 0.9996)$ for NVDSF I, and $V = 0.0044I^{0.33}$, $R^2 = 0.9997$ for NVDSF II (V is the volume flow rate (m^3/s) and I is the solar intensity (W/m^2) notwithstanding the slight decrease in breathing (which is minimal for intensities greater than $400\ W/m^2$ – averaged $5\ \%$ per $100\ W/m^2$, but increases in intensity at decreasing solar levels, averaged $26\ \%$ reduction per $100\ W/m^2$ for intensities lower than $400\ W/m^2$); (c) Mass flow rates over the 8 solar angles that exhibit a similar trend of fluctuation, (with the ventilation of air curtains remaining constant) $12 - 13\ \%$ higher, illustrated as a dendrogram of stacked hierarchical bands of machine-learning classifiers.

Results and discussion

Statistical inference

Air curtains are typically installed at the entrances of buildings to reduce the exchange of air owing to buoyancy [278]. Although these structures allow for unimpeded passage, there is a limited understanding of how the movement of both humans and vehicles interacts with air curtains [279]. To address this issue, small-scale water bath experiments have been conducted using fresh and saltwater solutions [280]. utilised a vertical cylinder to simulate human movement through an air curtain, which was created using a planar jet divided into 2 zones with different densities [5]. The results indicated that the average infiltration flow of the denser fluid on the lighter fluid side increased with a higher cylinder velocity at a constant travel distance both before and after the air curtain [8]. The sealing efficiency of the air curtain decreases as the cylinder speed increases, and this reduction is unaffected by the density disparity across the doorway or the direction of buoyancy-driven flow [34]. Dye visualisations were utilised to observe the re-establishment of the air curtain after being disrupted by the cylinder, focusing on both the air curtain and the cylinder wake [36]. The recovery time of the air curtain and the infiltration into the cylinder wake increased as the cylinder speed increased. The COVID-19 pandemic has highlighted the importance of understanding and controlling the transmission of SARS-CoV-2 among individuals [18]. conducted experimental and numerical investigations to study an advanced engineering and environmental method for regulating the spread of airborne SARS-CoV-2-laden aerosols in a confined space between 2 individuals during close interactions using air stability and ventilation [38]. Experiments were conducted in a full-scale ventilated chamber under various restricted space air stability conditions, including stable, neutral, and unstable settings [42]. Two individuals simulated normal breathing in a room using exhaled carbon dioxide as a substitute for airborne SARS-CoV-2-laden particles produced during respiratory activities [45]. A numerical model was developed to determine the temperature distribution and contamination level in a test room [50]. The effectiveness of a ventilation system in removing infectious airborne SARS-CoV-2-laden aerosols from the immediate breathing area between individuals relies on the air stability within confined spaces [51]. To maintain good air quality, it is essential to implement an appropriate ventilation method after assessing the air quality [51]. Total volume ventilation methods are recommended for unstable and neutral conditions, whereas local ventilation methods are preferred for stable conditions [52]. This study investigated the transmission of airborne SARS-CoV-2-laden aerosols between individuals in ventilated rooms with varying air stability [53]. The findings of this study provide valuable guidance for managing COVID-19 patients in confined areas.

Empirical validation

This investigation revealed that fluid characteristics and fragmentation behaviour have an impact on the transmission and contact phases of various pathogens and host systems [281]. The size, speed, and payload of pathogens or contaminants are selected to control the transport, persistence, and infectivity of pathogens during transmission between hosts [282]. Short-lived and unstable fluid fragmentation processes cause droplets to acquire time-varying features through interfacial instabilities, which are essential for assessing the contamination risk and limiting transmission [283]. In contrast, spray droplets have constant characteristics and are generated simultaneously [284]. When a drop impacts a target of a similar size, a 2D axisymmetric unsteady fragmentation process occurs, involving intricate, interconnected, and spatially and temporally changing multiscale nonlinear processes [285]. In subsequent sections, the evolution of the sheets and rims as well as the distributions of the droplet size and velocity are discussed [286]. The use of experimental techniques, precise feature extraction, tracking, and interfacial flow theory has elucidated the instabilities that determine the selection of droplet size and speed distributions in unstable fragmentation [287].

Error estimation

To accurately predict unstable droplet size and speed distributions, a comprehensive thickness profile is necessary along with a deeper understanding of rim dynamics and interconnected ligament-drop systems [13]. The thickness is inherently unstable, fluctuates over time, and is determined by the equilibrium between the incoming fluid from the expanding sheet and the outgoing fluid supplying the ligaments. A study by [288] showed that the linear stability analysis framework is incapable of depicting changes in the unstable thickness of the rim. Studying the behaviour of the unstable rim helps to solve the interconnected equations that control the sheet, rim, ligament, and droplets, leading to the ability to forecast the sizes and velocities of droplets in a specific 2D unstable fragmentation scenario [289]. The instability of the fragmentation process causes the droplet size and speed distributions to skew [290]. However, in the local non-inertial reference frame of the moving rim, the distributions are not skewed. [291] demonstrated that the droplet size and speed distributions during sheet expansion and retraction were symmetric and closely resembled the Gaussian distributions. The skewness of the cumulative distributions is a result of the unsteadiness in the sheet expansion, which causes superposition of instantaneous Gaussian distributions with time-evolving means [292]. This is crucial for developing a deterministic unified framework for researching unsteady fragmentation, which is essential for understanding pathogen contamination, emission, dispersal, persistence, and infection in new hosts in the context of disease transmission.

Unlike continuous fragmentation, empirical drop size distributions are typically modelled using log-normal, Poisson, exponential, Weibull-Rosin-Rammler, gamma, and compound gamma distributions [293]. These options all focus on measuring the asymmetry in the droplet size [294]. Some of these distributions, such as the log-normal and gamma distributions, are based on theoretical physical processes that control steady fluid fragmentation, whereas others are empirical curve fits [295]. The droplet generation problem can be simplified by isolating the impact of unsteadiness to understand the nonlinear instabilities that govern this type of multiscale unsteady fragmentation problem [296]. These problems involve ligament end pinching, which results in the creation of one drop at a time [297]. Furthermore, the foundational knowledge acquired has implications for several fields where irregular fragmentation is prevalent, including bloodstain effect patterns in criminology, medication delivery, product decontamination, and numerous industrial operations [298-327].

Conclusions

Studying the spread of diseases such as the 1918 flu epidemic, SARS, and COVID-19 is a complex and challenging task because of the rapid and unpredictable nature of these epidemics, which makes it difficult to test hypotheses and develop effective mitigation strategies. Historically, the transmission phase of infectious diseases has received little attention in scientific research. In 2020, they grappled with questions similar to those considered during the 1918 flu pandemic and the 2003 SARS outbreak, such as determining appropriate distances for social interactions and choosing the most effective masks for different situations. Furthermore, there is a limited understanding of the fluid dynamics that influence the spread of crop diseases in agricultural fields or the factors that affect food safety after harvesting. These knowledge gaps may be attributed to the perception of transmission as a complicated, transitory, and unpredictable process lacking a solid mechanical foundation. However, as transmission is a crucial part of a pathogen's life cycle, evolutionary forces favour the development of robust systems for this process. The cornerstone of every pandemic is the transfer of pathogens from one host to another. This principle offers a promising avenue for the formulation of strategies for managing and controlling the pandemic through medication and other means. In the past, controlling diseases such as smallpox, malaria, and typhoids seemed insurmountable. Initially, the mosquito theory of malaria was met with ridicule, indifference, envy, and rejection, when used to save human lives. Thankfully, the perseverance of many people has led to an increased confidence in achieving complete success. Ross and his colleagues introduced the idea of the epidemic reproduction number as a critical component in controlling malaria transmission. This approach focuses on managing the mosquito population and its interactions with humans, rather than attempting to eradicate mosquitoes entirely. Fluid physics play a crucial role in conducting precise quantitative measurements and gaining a comprehensive mechanistic understanding of host-to-host transmission. Progress can be made in tackling various infectious diseases before drugs or vaccines are developed.

This study aimed to establish a comprehensive interdisciplinary framework that can be utilised in anticipation and planning for pandemics that are likely to persist, reappear unexpectedly, and disappear. This framework aims to break down the transmission phase of the life cycle of a pathogen into a range of tractable multiscale fluid dynamics problems. These include the turbulent and particle-laden nature of exhalations, which shape the pathogen footprint of transmission relevant to respiratory diseases such as COVID-19 or influenza; the complex rheology of fluids and their fragmentation; the interplay between organisms and fluid phases that affect their dispersal and host-to-host transmission, including the stability of thin films to intrusions and the effects of subtle Marangoni flows on contaminated fluids; the fluid-surface interactions that are important for indoor contamination, agriculture, and food safety applications; and the common theme of unsteadiness, which governs the selection of contamination level, droplet size, and speed distributions via fragmentation, and shapes the pathogen footprint during transmission. This framework considers complex fluid-surface interactions, entangling compliance, surface wetting, and contaminant-fluid mixing and fragmentation. It also examines the effects of unsteadiness on the selection of the contamination level, droplet size, and speed distribution via fragmentation. This framework considers the common theme of unsteadiness, which governs the selection of the contamination level, droplet size, and speed distribution via fragmentation. Examples were selected from various healthcare fields to illustrate the wide range of fluid-related issues that impact people on a daily basis. Many interesting and numerous problems remain unresolved at every stage of infectious disease transmission and control, particularly regarding fluid dynamics. The topics covered included the benefits of using masks or innovative porous materials for source control, the risk of host invasion through droplet nuclei via the conjunctiva, the potential benefits of using face shields in combination with face masks, the impact of environmental conditions on indoor and outdoor phase changes, and the consequences of these conditions on transmission and pathogen survival. This study discusses how fluid dynamics related to COVID-19 can influence infection control measures; return-to-work strategies; medical procedures; artistic activities involving fluids and respiratory flows; hand washing; social distancing in different environments; redesigning indoor spaces such as offices, schools, factories, airplanes, or trains; and advancements in surface and air decontamination. Precise laboratory experiments and modelling can provide valuable insights for creating and confirming customised solutions for natural or artificial ventilation and indoor air management systems. These solutions are designed to suit specific space usages, occupancy levels, and durations. Detailed airflow patterns, rather than average ventilation rates, play a crucial role in reducing transmission risks.

Flow heterogeneities have been linked to localised infection clusters because the well-mixed limit of ventilation only offers the minimum pathogen dilution level, setting the lowest exposure risk in an indoor area. Fluid-based multiscale modelling can help understand pollution and infection risks, guide adaptive mitigation techniques, and facilitate the discovery of novel medications targeting crucial pathways in fluid-based transmission. For example, there is a need for further clarification of the rheology of biological fluids. External additives can be used to alter fluid characteristics to decrease a pathogen's attraction to certain fluids to adhere to surfaces, whether biological or physical, or diminish the capacity of the fluid to spread pathogens. These innovative uses in health and infectious illnesses have led to the exploration of novel fluid processes, and have driven the creation of new instruments with broader applicability outside their initial health-related contexts. Breakthroughs in image processing techniques have provided key insights into unstable fragmentation. These advancements are further supported by theories aimed at understanding the transmission of pathogens. The discovery of organisms manipulating surface bubbles for improved water-to-air dispersal, despite the absence of bacteria affecting surface tension, has enhanced the understanding of interfacial film dynamics and the impact of Marangoni flow. This advancement could lead to the development of new methods for studying complicated, multiphase, and multiscale transient flows at interfaces, with a focus on emerging issues at the junction of fluids and health. In light of the rapid development of this new field, it is essential to refine and employ well-established fluid dynamics approaches because of their proven track record of minimal error tolerance in critical sectors, such as aeronautics and astronautics, where human lives are at stakeholders, and the use of a hollow vortex ring to represent violent human exhalations, instead of a point-source turbulent puff, which can result in inaccuracies in the range, mixing, and phase-change behaviour of droplets carrying pathogens. This approach also fails to accurately capture the pathogen footprint, which is crucial for a precise risk assessment.

High-fidelity numerical tools in frontier areas benefit significantly from validation using high-precision and rigorous experimental data. Accurate forecasting supported by thorough validation is crucial for advancing the subject of the Fluid Dynamics of Disease Transmission and for improving infectious disease surveillance, control, and prevention, which are essential for saving lives. The discovery of various intriguing processes of interactions between life and physics, such as interfacial, multiphase, and complex flows, will provide new opportunities for understanding the ecological or evolutionary limitations that have been overlooked because of the uninvestigated fluid dynamics that control the dispersion and transmission activities of microorganisms. Understanding these connections will lead to new and fascinating insights into the evolutionary forces affecting helpful, neutral, and harmful organisms, and thus, life as a whole.

Conflicts of interest

No financial or institutional support was involved in the preparation of this paper. The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper is very dear to the author as it is a manifestation of several years of hard work and patience. It is the author’s own, independent, and original work, and complies with all publishing ethics.

References

[1] J Adams, K Agyenkwa-Mawuli, O Agyapong, MD Wilson and SK Kwofie. EBOLApred: A machine learning-based web application for predicting cell entry inhibitors of the Ebola virus. *Comput. Biol. Chem.* 2022; **101**, 107766.

[2] N Agarwal, CS Meena, BP Raj, L Saini, A Kumar, N Gopalakrishnan, A Kumar, NB Balam, T Alam, NR Kapoor and V Aggarwal. Indoor air quality improvement in COVID-19 pandemic: Review. *Sustain. Cities Soc.* 2021; **70**, 102942.

[3] AJ Aguilar, MLDL Hoz-Torres, MD Martínez-Aires and DP Ruiz. Monitoring and assessment of indoor environmental conditions after the implementation of COVID-19-based ventilation strategies in an educational building in southern Spain. *Sensors* 2021; **21**, 7223.

[4] F Ahmed, IS Kang, KH Kim, A Asif, CSA Rahim, A Samantasinghar, FH Memon and KH Choi. Drug repurposing for viral cancers: A paradigm of machine learning, deep learning, and virtual screening-based approaches. *J. Med. Virol.* 2023; **95**, e28693.

[5] T Ahmed, HE Wendling, AA Mofakham, G Ahmadi, BT Helenbrook, AR Ferro, DM Brown and BD Erath. Variability in expiratory trajectory angles during consonant production by one human subject and from a physical mouth model: Application to respiratory droplet emission. *Indoor Air* 2021; **31**, 1896-912.

[6] ZT Ai and AK Melikov. Airborne spread of expiratory droplet nuclei between the occupants of indoor environments: A review. *Indoor Air* 2018; **28**, 500-24.

[7] S Aich, KW Choi, PM Pradhan, J Park and HC Kim. Prediction of neurodegenerative diseases based on gait signals using supervised machine learning techniques. *Adv. Sci. Lett.* 2018; **24**, 1974-8.

[8] A Alaidroos, A Almaimani, A Baik, M Al-Amodi and KR Rahaman. Are historical buildings more adaptive to minimize the risks of airborne transmission of viruses and public health? A study of the hazzazi house in Jeddah (Saudi Arabia). *Int. J. Environ. Res. Publ. Health* 2021; **18**, 3601.

[9] SA Suha and MN Islam. Exploring the dominant features and data-driven detection of polycystic ovary syndrome through modified stacking ensemble machine learning technique. *Heliyon* 2023; **9**, e14518.

[10] S Algarni, RA Khan, NA Khan and NM Mubarak. Particulate matter concentration and health risk assessment for a residential building during COVID-19 pandemic in Abha, Saudi Arabia. *Environ. Sci. Pollut. Res.* 2021; **28**, 65822-31.

[11] AY Alhaddad, H Aly, H Gad, A Al-Ali, KK Sadasivuni, JJ Cabibihan and RA Malik. Sense and learn: Recent advances in wearable sensing and machine learning for blood glucose monitoring and Trend-Detection. *Front. Bioeng. Biotechnol.* 2022; **10**, 699.

[12] MK Ali, S Javaid, H Afzal, I Zafar, K Fayyaz, QU Ain, MA Rather, MJ Hossain, S Rashid, KA Khan and R Sharma. Exploring the multifunctional roles of quantum dots for unlocking the future of biology and medicine. *Environ. Res.* 2023; **232**, 116290.

[13] Y Alimohamadi, HH Tola, A Abbasi-Ghahramanloo, M Janani and M Sepandi. Case fatality rate of COVID-19: A systematic review and meta-analysis. *J. Prev. Med. Hyg.* 2021; **62**, E311-E320.

[14] A Alonso, J Llanos, R Escandón and JJ Sendra. Effects of the covid-19 pandemic on indoor air quality and thermal comfort of primary schools in winter in a mediterranean climate. *Sustainability* 2021; **13**, 2699.

[15] Z Alqarni, Y Rezgui, I Petri and A Ghoroghi. Viral infection transmission and indoor air quality: A systematic review. *Sci. Total Environ.* 2024; **923**, 171308.

[16] HH Alsaadi, M Aldwairi, F Yasin, SCP Cachinho and A Hussein. Artificial intelligence tool for the study of COVID-19 microdroplet spread across the human diameter and airborne space. *PLos One* 2023; **18**, e0269905.

[17] EG Al-Sakkari, A Ragab, H Dagdougui, DC Boffito and M Amazouz. Carbon capture, utilization and sequestration systems design and operation optimization: Assessment and perspectives of artificial intelligence opportunities. *Sci. Total Environ.* 2024; **917**, 170085.

[18] L Álvarez-Pomar and S Rojas-Galeano. Impact of personal protection habits on the spread of pandemics: Insights from an Agent-Based model. *Sci. World J.* 2021; **2021**, 6616654.

[19] S Anand and YS Mayya. Size distribution of virus laden droplets from expiratory ejecta of infected subjects. *Sci. Rep.* 2020; **10**, 21174.

[20] BA Fezi. *The role of architecture and urbanism in preventing pandemics*. Origin and Impact of COVID-19 Pandemic Originating from SARS-CoV-2 Infection Across the Globe. IntechOpen, London, 2021.

[21] CD Argyropoulos, V Skoulou, G Efthimiou and AK Michopoulos. Airborne transmission of biological agents within the indoor built environment: A multidisciplinary review. *Air Qual. Atmosphere Health* 2023; **16**, 477-533.

[22] V Arumuru, J Pasa and SS Samantaray. Experimental visualization of sneezing and efficacy of face masks and shields. *Phys. Fluid.* 2020; **32**, 115129.

[23] JA Prakash, C Asswin, V Ravi, V Sowmya and K Soman. Pediatric pneumonia diagnosis using stacked ensemble learning on multi-model deep CNN architectures. *Multimed. Tool. Appl.* 2023; **82**, 21311-51.

[24] SS Arya, SB Dias, HF Jelinek, LJ Hadjileontiadis and AM Pappa. The convergence of traditional and digital biomarkers through AI-assisted biosensing: A new era in translational diagnostics? *Biosens. Bioelectron.* 2023; **235**, 115387.
[25] S Asadi, AS Wexler, CD Cappa, S Barreda, NM Bouvier and WD Ristenpart. Aerosol emission and superemission during human speech increase with voice loudness. *Sci. Rep.* 2019; **9**, 2348.
[26] HC Ates, PQ Nguyen, L Gonzalez-Macia, E Morales-Narváez, F Güder, JJ Collins and C Dincer. End-to-end design of wearable sensors. *Nat. Rev. Mater.* 2022; **7**, 887-907.
[27] M Auvinen, J Kuula, T Grönholm, M Sühring and A Hellsten. High-resolution large-eddy simulation of indoor turbulence and its effect on airborne transmission of respiratory pathogens-Model validation and infection probability analysis. *Phys. Fluid.* 2022; **34**, 015124.
[28] D Aviv, KW Chen, E Teitelbaum, D Sheppard, J Pantelic, A Rysanek and F Meggers. A fresh (air) look at ventilation for COVID-19: Estimating the global energy savings potential of coupling natural ventilation with novel radiant cooling strategies. *Appl. Energ.* 2021; **292**, 116848.
[29] Z Baboli, N Neisi, AA Babaei, M Ahmadi, A Sorooshian, YT Birgani and G Goudarzi. On the airborne transmission of SARS-CoV-2 and relationship with indoor conditions at a hospital. *Atmos. Environ.* 2021; **261**, 118563.
[30] A Bahramian. Influence of indoor environmental conditions on airborne transmission and lifetime of sneeze droplets in a confined space: A way to reduce COVID-19 spread. *Environ. Sci. Pollut. Res.* 2023; **30**, 44067-85.
[31] A Bahramian, M Mohammadi and G Ahmadi. Effect of indoor temperature on the velocity fields and airborne transmission of sneeze droplets: An experimental study and transient CFD modeling. *Sci. Total Environ.* 2023; **858**, 159444.
[32] S Balachandar, S Zaleski, A Soldati, G Ahmadi and L Bourouiba. Host-to-host airborne transmission as a multiphase flow problem for science-based social distance guidelines. *Int. J. Multiphas. Flow* 2020; **132**, 103439.
[33] AK Azad. *Advances in clean energy technologies*. Copyright, Washington DC, 2020.
[34] MZ Bazant and JWM Bush. A guideline to limit indoor airborne transmission of COVID-19. *Proc. Natl. Acad. Sci. Unit. States Am.* 2021; **118**, e2018995118.
[35] M Beaussier, E Vanoli, F Zadegan, H Peray, E Bezian, J Jilesen, G Gandveau and JM Gayraud. Aerodynamic analysis of hospital ventilation according to seasonal variations. A simulation approach to prevent airborne viral transmission pathway during Covid-19 pandemic. *Environ. Int.* 2022; **158**, 106872.
[36] R Bhardwaj and A Agrawal. Likelihood of survival of coronavirus in a respiratory droplet deposited on a solid surface. *Phys. Fluid.* 2020; **32**, 61704.
[37] A Bhattacharya, A Ghahramani and E Mousavi. The effect of door opening on air-mixing in a positively pressurized room: Implications for operating room air management during the COVID outbreak. *J. Build. Eng.* 2021; **44**, 102900.
[38] KR Bhimala, GK Patra, R Mopuri and SR Mutheneni. Prediction of COVID-19 cases using the weather integrated deep learning approach for India. *Transboundary Emerg. Dis.* 2022; **69**, 1349-63.
[39] P Bloomingdale, D Bumbaca-Yadav, J Sugam, S Grauer, B Smith, S Antonenko, M Judo, G Azadi and KL Yee. PBPK-PD modeling for the preclinical development and clinical translation of tau antibodies for Alzheimer’s disease. *Front. Pharmacol.* 2022; **13**, 867457.
[40] W Bovenizer and P Chetthamrongchai. A comprehensive systematic and bibliometric review of the IoT-based healthcare systems. *Cluster Comput.* 2023; **26**, 3291-317.
[41] R Brady and H Enderling. Mathematical models of cancer: When to predict novel therapies, and when not to. *Bull. Math. Biol.* 2019; **81**, 3722-31.
[42] A Brodeur, D Gray, A Islam and S Bhuiyan. A literature review of the economics of COVID-19. *J. Econ. Surv.* 2021; **35**, 1007-44.
[43] G Buonanno, L Morawska and L Stabile. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications. *Environ. Int.* 2020; **145**, 106112.
[44] G Buonanno, L Stabile and L Morawska. Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. *Environ. Int.* 2020; **141**, 105794.
[45] E Burgos-Ramos, IR Urbieta and D Rodríguez. Is hydrogen peroxide an effective mouthwash for reducing the viral load of SARS-CoV-2 in dental clinics? *Saudi Dent. J.* 2022; **34**, 237-42.
[46] HC Burridge, S Fan, RL Jones, CJ Noakes and PF Linden. Predictive and retrospective modelling of airborne infection risk using monitored carbon dioxide. *Indoor Built Environ.* 2022; **31**, 1363-80.

[47] CM Calama-González, ÁL León-Rodríguez and R Suárez. Indoor environmental assessment: Comparing ventilation scenarios in pre- and post-retrofitted dwellings through test cells. *J. Build. Eng.* 2021; **43**, 103148.
[48] FC Peralvo, PC Vanegas and E Avila-Ordóñez. A systematic review of COVID-19 transport policies and mitigation strategies around the globe. *Transport. Res. Interdiscipl. Perspect.* 2022; **15**, 100653.
[49] A Cammarata and G Cammarata. Dynamic assessment of the risk of airborne viral infection. *Indoor Air* 2021; **31**, 1759-75.
[50] EC Mutlu, M Kaya, I Küçük, B Ben-Nissan and A Stamboulis. Exosome structures supported by machine learning can be used as a promising diagnostic tool. *Materials* 2022; **15**, 7967.
[51] M Carmona. *Public places urban spaces*. Routledge, New York, 2021.
[52] M Casini. Extended reality for smart building operation and maintenance: A review. *Energies* 2022; **15**, 3785.
[53] FC Martínez, G Peris-Fajarnes, PM Camo, IL Lengua and BD García. Advances in design engineering II. *In*: Proceedings of the XXX International Congress INGEGRAF, Valencia, Spain. 2021.
[54] MR Challapa-Mamani, E Tomás-Alvarado, A Espinoza-Baigorria, DA León-Figueroa, R Sah, AJ Rodriguez-Morales and JJ Barboza. Molecular docking and molecular dynamics simulations in related to leishmania donovani: An update and literature review. *Trop. Med. Infect. Dis.* 2023; **8**, 457.
[55] R Chandrasekaran, K Konaraddi, SS Sharma and E Moustakas. Text-Mining and video analytics of covid-19 narratives shared by patients on youtube. *J. Med. Syst.* 2024; **48**, 21.
[56] S Chaudhuri, S Basu, P Kabi, VR Unni and A Saha. Modeling the role of respiratory droplets in Covid-19 type pandemics. *Phys. Fluid.* 2020; **32**, 63309.
[57] L Chen, G Ban, E Long, G Kalonji, Z Cheng, L Zhang and S Guo. Estimation of the SARS-CoV-2 transmission probability in confined traffic space and evaluation of the mitigation strategies. *Environ. Sci. Pollut. Res.* 2021; **28**, 42204-16.
[58] LD Chen. Effects of ambient temperature and humidity on droplet lifetime - A perspective of exhalation sneeze droplets with COVID-19 virus transmission. *Int. J. Hyg. Environ. Health* 2020; **229**, 113568.
[59] M Chen, J Yang, C Tang, X Lu, Z Wei, Y Liu, P Yu and H Li. Improving ADMET prediction accuracy for candidate drugs: Factors to consider in QSPR modeling approaches. *Curr. Top. Med. Chem.* 2023; **24**, 222-42.
[60] Y Cheng, T Chen and J Hu. Genetic analysis of potential biomarkers and therapeutic targets in neuroinflammation from sporadic Creutzfeldt-Jakob disease. *Sci. Rep.* 2023; **13**, 14122.
[61] E Chrysikou, EH Garcia and E Savvopoulou. *International research project on emergency response to infectious disease outbreak on cruise ships*. The Bartlett Real Estate Institute UCI, London, 2021.
[62] D Coclite, A Napoletano, S Gianola, AD Monaco, D D'Angelo, A Fauci, L Iacorossi, R Latina, GL Torre, CM Mastroianni, C Renzi, G Castellini and P Iannone. Face mask use in the community for reducing the spread of covid-19: A systematic review. *Front. Med.* 2021; **7**, 594269.
[63] MO Coppens. Nature-Inspired chemical engineering for process intensification. *Annu. Rev. Chem. Biomol. Eng.* 2021; **12**, 187-215.
[64] PR Corridon, X Wang, A Shakeel and V Chan. Digital technologies: Advancing individualized treatments through gene and cell therapies, pharmacogenetics, and disease detection and diagnostics. *Biomedicines* 2022; **10**, 2445.
[65] JP Coyle, RC Derk, WG Lindsley, FM Blachere, T Boots, AR Lemons, SB Martin, KR Mead, SA Fotta, JS Reynolds, WG McKinney, EW Sinsel, DH Beezhold and JD Noti. Efficacy of ventilation, HEPA air cleaners, universal masking, and physical distancing for reducing exposure to simulated exhaled aerosols in a meeting room. *Viruses* 2021; **13**, 2536.
[66] DH Crawford. *Viruses: The invisible enemy*. Oxford University Press, Oxford, 2021.
[67] KM Crofton, A Bassan, M Behl, YG Chushak, E Fritsche, JM Gearhart, MS Marty, M Mumtaz, M Pavan, P Ruiz, M Sachana, R Selvam, TJ Shafer, L Stavitskaya, DT Szabo, ST Szabo, RR Tice, D Wilson, D Woolley and GJ Myatt. Current status and future directions for a neurotoxicity hazard assessment framework that integrates *in silico* approaches. *Comput. Toxicol.* 2022; **22**, 100223.
[68] Z Cui, M Cai, Y Xiao, Z Zhu and G Chen. Influences of obstacle factors on the transmission trends of respiratory infectious diseases in indoor public places. *J. Build. Eng.* 2023; **64**, 105706.
[69] P Dacunto, D Moser, A Ng and M Benson. Classroom aerosol dispersion: Desk spacing and divider impacts. *Int. J. Environ. Sci. Tech.* 2022; **19**, 1057-70.
[70] M Dai, G Xiao, M Shao and YS Zhang. The synergy between deep learning and organs-on-chips for high-throughput drug screening: A review. *Biosensors* 2023; **13**, 389.

[71] ED Filippi, T Marins, A Escrichs, M Gilson, J Moll, F Tovar-Moll and G Deco. One session of fMRI-Neurofeedback training on motor imagery modulates whole-brain effective connectivity and dynamical complexity. *Cerebr. Cortex Comm.* 2022; **3**, 1-13.

[72] FD Frutos, T Cuerdo-Vilches, C Alonso, F Martín-Consuegra, B Frutos, I Oteiza and MÁ Navas-Martín. Indoor environmental quality and consumption patterns before and during the covid–19 lockdown in Twelve social dwellings in Madrid, Spain. *Sustainability* 2021; **13**, 7700.

[73] MLDL Hoz-Torres, AJ Aguilar, DP Ruiz and MD Martínez-Aires. Analysis of impact of natural ventilation strategies in ventilation rates and indoor environmental acoustics using sensor measurement data in educational buildings. *Sensors* 2021; **21**, 6122.

[74] SOD Souza, AA Cardoso, ASC Sarmento and F D'Errico. Effectiveness of a UVC air disinfection system for the HVAC of an ICU. *Eur. Phys. J. Plus* 2022; **137**, 37.

[75] BBVL Deepak, DRK Parhi, BB Biswal and PC Jena. *Applications of computational methods in manufacturing and product design*. Springer, Gateway East, Singapore, 2020.

[76] MD Giudice and BJ Crespi. Basic functional trade-offs in cognition: An integrative framework. *Cognition* 2018; **179**, 56-70.

[77] K Demertzis, D Taketzis, V Demertzi and C Skianis. An ensemble transfer learning spiking immune system for adaptive smart grid protection. *Energies* 2022; **15**, 4398.

[78] AK Deol, D Scarponi, P Beckwith, TA Yates, AS Karat, AWC Yan, KS Baisley, AD Grant, RG White and N McCreesh. Estimating ventilation rates in rooms with varying occupancy levels: Relevance for reducing transmission risk of airborne pathogens. *PLos One* 2021; **16**, e0253096.

[79] D Desai and P Shende. Integration of internet of things with quantum dots: A State-of-the-art of medicine. *Curr. Pharmaceut. Des.* 2021; **27**, 2068-75.

[80] R Dhand and J Li. Coughs and sneezes: Their role in transmission of respiratory viral infections, including SARS-CoV-2. *Am. J. Respir. Crit. Care Med.* 2020; **202**, 651-9.

[81] AD Gilio, J Palmisani, M Pulimeno, F Cerino, M Cacace, A Miani and GD Gennaro. CO_2 concentration monitoring inside educational buildings as a strategic tool to reduce the risk of Sars-CoV-2 airborne transmission. *Environ. Res.* 2021; **202**, 111560.

[82] P Diez, P Neittaanmäki, J Periaux, T Tuovinen and J Pons-Prats. *Computation and big data for transport*. Springer, Cham, Germany, 2020.

[83] S Dihan, AI Akash, Z Tasneem, P Das, SK Das, R Islam, M Islam, FR Badal, F Ali, H Ahamed, SH Abhi, SK Sarker and M Hasan. Digital twin: Data exploration, architecture, implementation and future. *Heliyon* 2024; **10**, e26503.

[84] SP Domino. A case study on pathogen transport, deposition, evaporation and transmission: Linking high-fidelity computational fluid dynamics simulations to probability of infection. *Int. J. Comput. Fluid Dynam.* 2021; **35**, 743-57.

[85] Y Dong, L Zhu, S Li and M Wollensak. Optimal design of building openings to reduce the risk of indoor respiratory epidemic infections. *Build. Simulat.* 2022; **15**, 871-84.

[86] F. F Duill, F Schulz, A Jain, L Krieger, BV Wachem and F Beyrau. The impact of large mobile air purifiers on aerosol concentration in classrooms and the reduction of airborne transmission of sars-cov-2. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 11523.

[87] RM Elavarasan, R Pugazhendhi, GM Shafiullah, M Irfan and A Anvari-Moghaddam. A hover view over effectual approaches on pandemic management for sustainable cities - The endowment of prospective technologies with revitalization strategies. *Sustain. Cities Soc.* 2021; **68**, 102789.

[88] H Elnimr. Assessing alzheimer's therapeutic environment digitally through a people with alzheimer's' disease perspective: A computation-based approach framework. *Buildings* 2023; **13**, 2232.

[89] F Falahati, E Westman and A Simmons. Multivariate data analysis and machine learning in Alzheimer's disease with a focus on structural magnetic resonance imaging. *J. Alzheimer's Dis.* 2014; **41**, 685-708.

[90] MI Farouk, AF Nassar and MH Elgamal. Numerical study of the transmission of exhaled droplets between the instructor and students in a typical classroom. *Appl. Sci.* 2021; **11**, 9767.

[91] TS Farthing and C Lanzas. Assessing the efficacy of interventions to control indoor SARS-Cov-2 transmission: An agent-based modeling approach. *Epidemics* 2021; **37**, 100524.

[92] R Fayos-Jordan, J Segura-Garcia, A Soriano-Asensi, S Felici-Castell, JM Felisi and JM Alcaraz-Calero. VentQsys: Low-cost open IoT system for CO2 monitoring in classrooms. *Wireless Network.* 2021; **27**, 5313-27.

[93] L Feng, Y Niu and J Wang. Development of morphology analysis-based technology roadmap considering layer expansion paths: Application of triz and text mining. *Appl. Sci.* 2020; **10**, 8498.

[94] Y Feng, T Marchal, T Sperry and H Yi. Influence of wind and relative humidity on the social distancing effectiveness to prevent COVID-19 airborne transmission: A numerical study. *J. Aerosol Sci.* 2020; **147**, 105585.
[95] Y Feng, Y Zhang, X Ding, Y Fan and J Ge. Multi-scale risk assessment and mitigations comparison for COVID-19 in urban public transport: A combined field measurement and modeling approach. *Build. Environ.* 2023; **242**, 110489.
[96] S Ferrari, T Blázquez, R Cardelli, G Puglisi, R Suárez and L Mazzarella. Ventilation strategies to reduce airborne transmission of viruses in classrooms: A systematic review of scientific literature. *Build. Environ.* 2022; **222**, 109366.
[97] M Fisun and H Horban. Implementation of the information system of the association rules generation from OLAP-cubes in the post-relational DBMS caché. *In*: Proceedings of the 2016 XIth International Scientific and Technical Conference Computer Sciences and Information Technologies, Lviv, Ukraine. 2016.
[98] AS Fokas, N Dikaios and GA Kastis. Mathematical models and deep learning for predicting the number of individuals reported to be infected with SARS-CoV-2. *J. R. Soc. Interface.* 2020; **17**, 20200494.
[99] J Fottner, K Nübel and D Matt. *Construction logistics, equipment, and robotics*. Springer, Cham, Germany, 2024.
[100] S Ganesh, T Chithambaram, NR Krishnan, DR Vincent, J Kaliappan and K Srinivasan. Exploring huntington's disease diagnosis via artificial intelligence models: A comprehensive review. *Diagnostics* 2023; **13**, 3592.
[101] X Gao, Q Lv and S Hou. Progress in the application of portable ultrasound combined with artificial intelligence in pre-hospital emergency and disaster sites. *Diagnostics* 2023; **13**, 3388.
[102] G Yong-jun, W Song, JL Liu and S Bashir. *Advances in sustainable energy*. Springer, Cham, Germany, 2021.
[103] SG Gehrke, C Förderer, R Weiskirchen and W Stremmel. Cold traps as reliable devices for quantitative determination of SARS-CoV-2 load in aerosols. *Environ. Monit. Assess.* 2021; **193**, 778.
[104] CL Geng, XY Zhu and N Chen. Optimizing indoor air quality: CFD simulation and novel air cleaning methods for effective aerosol particle inhibition in public spaces. *Environ. Sci. Pollut. Res. Int.* 2023; **30**, 120528-39.
[105] A Georgas, K Georgas and E Hristoforou. Advancements in SARS-CoV-2 testing: Enhancing accessibility through machine learning-enhanced biosensors. *Micromachines* 2023; **14**, 1518.
[106] M Ghafoori, C Clevenger, M Abdallah and K Rens. Heart rate modeling and prediction of construction workers based on physical activity using deep learning. *Autom. Construct.* 2023; **155**, 105077.
[107] A Ghoroghi, Y Rezgui and R Wallace. Impact of ventilation and avoidance measures on SARS-CoV-2 risk of infection in public indoor environments. *Sci. Total Environ.* 2022; **838**, 156518.
[108] K Gkiotsalitis and O Cats. Optimal frequency setting of metro services in the age of COVID-19 distancing measures. *Transportmetrica A Transport Sci.* 2022; **18**, 807-27.
[109] C Gomes and M Rautureau. *Minerals latu sensu and human health*. Springer, Cham, Germany, 2021.
[110] AG Correia, M Azenha, PJS Cruz, P Novais and P Pereira. *Trends on construction in the digital era*. Springer, Cham, Germany, 2022.
[111] J Gomez, J Prieto, E Leon and A Rodríguez. INFEKTA-An agent-based model for transmission of infectious diseases: The COVID-19 case in Bogotá, Colombia. *PLos One* 2021; **16**, e0245787.
[112] M Grassi, N Rouleaux, D Caldirola, D Loewenstein, K Schruers, G Perna and M Dumontier. A novel ensemble-based machine learning algorithm to predict the conversion from mild cognitive impairment to Alzheimer's disease using socio-demographic characteristics, clinical information, and neuropsychological measures. *Front. Neurol.* 2019; **10**, 756.
[113] JO Grimalt, H Vílchez, PA Fraile-Ribot, E Marco, A Campins, J Orfila, BLV Drooge and F Fanjul. Spread of SARS-CoV-2 in hospital areas. *Environ. Res.* 2022; **204**, 11207.
[114] W Guo, K Qian, H Tang and L Gong. *Proceedings of the 2023 international conference on green building, civil engineering and smart city*. Springer, Gateway East, Singapore, 2024.
[115] Y Gupta, RK Lama and GR Kwon. Prediction and classification of alzheimer's disease based on combined features from apolipoprotein-E genotype, cerebrospinal fluid, MR, and FDG-PET imaging biomarkers. *Front. Comput. Neurosci.* 2019; **13**, 72.
[116] N Habibi, S Uddin, F Al-Salameen, S Al-Amad, V Kumar, M Al-Otaibi, NA Razzack, A Shajan and F Shirshikar. SARS-CoV-2, other respiratory viruses and bacteria in aerosols: Report from Kuwait's hospitals. *Indoor Air* 2021; **31**, 1815-25.

[117] W Hao and A Friedman. Mathematical model on Alzheimer's disease. *BMC Syst. Biol.* 2016; **10**, 108.
[118] T Harweg, D Bachmann and F Weichert. Agent-based simulation of pedestrian dynamics for exposure time estimation in epidemic risk assessment. *J. Publ. Health* 2023; **31**, 221-8.
[119] AE Hassanien, A Darwish and V Snasel. *Digital twins for digital transformation: Innovation in industry*. Springer, Cham, Germany, 2022.
[120] S Hemati, GR Mobini, M Heidari, F Rahmani, AS Babadi, M Farhadkhani, H Nourmoradi, A Raeisi, A Ahmadi, A Khodabakhshi, M Sadeghi, M Bagheri, M Validi, S Taghipour and F Mohammadi-Moghadam. Simultaneous monitoring of SARS-CoV-2, bacteria, and fungi in indoor air of hospital: A study on Hajar Hospital in Shahrekord, Iran. *Environ. Sci. Pollut. Res.* 2021; **28**, 43792-802.
[121] CI Hernandez, S Kargarnovin, S Hejazi and W Karwowski. Examining electroencephalogram signatures of people with multiple sclerosis using a nonlinear dynamics approach: A systematic review and bibliographic analysis. *Front. Comput. Neurosci.* 2023; **17**, 1207067.
[122] B Hong, BJ Bonczak, A Gupta, LE Thorpe and CE Kontokosta. Exposure density and neighborhood disparities in COVID-19 infection risk. *Proc. Natl. Acad. Sci. Unit. States Am.* 2021; **118**, e2021258118.
[123] PF Horve, LG Dietz, M Fretz, DA Constant, A Wilkes, JM Townes, RG Martindale, WB Messer and KGVD Wymelenberg. Identification of SARS-CoV-2 RNA in healthcare heating, ventilation, and air conditioning units. *Indoor Air* 2021; **31**, 1826-32.
[124] F Hou, J Ma, HHL Kwok and JCP Cheng. Prediction and optimization of thermal comfort, IAQ and energy consumption of typical air-conditioned rooms based on a hybrid prediction model. *Build. Environ.* 2022; **225**, 109576.
[125] B Hu, ZH Guan, G Chen and CLP Chen. Neuroscience and network dynamics toward brain-inspired intelligence. *IEEE Trans. Cybern.* 2022; **52**, 10214-27.
[126] M Hu, Y Yu, F He, Y Su, K Zhang, X Liu, P Liu, Y Liu, G Peng and B Luo. Classification and interpretability of mild cognitive impairment based on resting-state functional magnetic resonance and ensemble learning. *Comput. Intell. Neurosci.* 2022; **2022**, 2535954.
[127] Q Huang, T Marzouk, R Cirligeanu, H Malmstrom, E Eliav and YF Ren. Ventilation assessment by carbon dioxide levels in dental treatment rooms. *J. Dent. Res.* 2021; **100**, 810-6.
[128] TC Hung, WY Lee, KB Chen, YC Chan and CYC Chen. Lead screening for HIV-1 integrase (IN) inhibited by traditional Chinese medicine. *BioMed Res. Int.* 2014; **2014**, 479367.
[129] T Hussein, J Löndahl, S Thuresson, M Alsved, A Al-Hunaiti, K Saksela, H Aqel, H Junninen, A Mahura and M Kulmala. Indoor model simulation for covid-19 transport and exposure. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 2927.
[130] K Inthavong. Message from the guest editor of the SCONA 2022 meeting special issue. *Exp. Comput. Multiphas. Flow* 2023; **5**, 233-4.
[131] IMI Ismail, MI Rashid, N Ali, BAS Altaf and M Munir. Temperature, humidity and outdoor air quality indicators influence COVID-19 spread rate and mortality in major cities of Saudi Arabia. *Environ. Res.* 2022; **204**, 112071.
[132] ZA Ismail. Machine learning applications for a better demand controlled ventilation system experience in buildings: A review. *Open House Int.* 2023, https://doi.org/10.1108/OHI-03-2023-0065.
[133] K Ito. Toward the development of an *in silico* human model for indoor environmental design. *Proc. Jpn. Acad. B Phys. Biol. Sci.* 2016; **92**, 185-203.
[134] F Jiang, J Ma, CJ Webster, AJF Chiaradia, Y Zhou, Z Zhao and X Zhang. Generative urban design: A systematic review on problem formulation, design generation, and decision-making. *Progr. Plann.* 2024; **180**, 100795.
[135] MP Kain, ML Childs, AD Becker and EA Mordecai. Chopping the tail: How preventing superspreading can help to maintain COVID-19 control. *Epidemics* 2021; **34**, 100430.
[136] S Kanchi, R Chokkareddy and M Rezakazemi. *Smart nanodevices for Point-of-Care applications*. CRC Press, Florida, 2022.
[137] NR Kapoor, A Kumar, A Kumar, A Kumar and HC Arora. *Prediction of indoor air quality using artificial intelligence*. *In*: A Kumar, M Bhushan, JA Galindo, L Garg and H Yu-Chen (Eds.). Machine Intelligence, Big Data Analytics, and IoT in Image Processing: Practical Applications. Wiley, New Jersey, 2023, p. 447-69.
[138] N Kappelt, HS Russell, S Kwiatkowski, A Afshari and MS Johnson. Correlation of respiratory aerosols and metabolic carbon dioxide. *Sustainability* 2021; **13**, 12203.
[139] N Karballaeezadeh, S Danial Mohammadzadeh, M Mudabbiruddin and AH Rad. Modeling road roughness through vibration analysis for driving quality and extended discussion on AI potential. *In*:

Proceedings of the 2023 IEEE 17th International Symposium on Applied Computational Intelligence and Informatics, Timisoara, Romania. 2023.
[140] V Karunakaran, MM Joseph, I Yadev, H Sharma, K Shamna, S Saurav, RP Sreejith, V Anand, R Beegum, SR David, T Iype, KLS Devi, A Nizarudheen, MS Sharmad, R Sharma, R Mukhiya, E Thouti, K Yoosaf, J Joseph, PS Devi, …, KK Maiti. A non-invasive ultrasensitive diagnostic approach for COVID-19 infection using salivary label-free SERS fingerprinting and artificial intelligence. *J. Photochem. Photobiol. B Biol.* 2022; **234**, 112545.
[141] P Katre, S Banerjee, S Balusamy and KC Sahu. Fluid dynamics of respiratory droplets in the context of COVID-19: Airborne and surfaceborne transmissions. *Phys. Fluid.* 2021; **33**, 81302.
[142] MA Kazem. Predictive models in cancer management: A guide for clinicians. *Surgeon* 2017; **15**, 93-7.
[143] K Ito, K Inthavong, T Kurabuchi, T Ueda, T Endo, T Omori, H Ono, S Kato, K Sakai, Y Suwa, H Matsumoto, H Yoshino, W Zhang and J Tu. CFD benchmark tests for indoor environmental problems: Part 1 isothermal/non-isothermal flow in 2D and 3D room model. *Int. J. Architect. Eng. Tech.* 2015; **2**, 1-22.
[144] K Ito, K Inthavong, T Kurabuchi, T Ueda, T Endo, T Omori, H Ono, S Kato, K Sakai, Y Suwa, H Matsumoto, H Yoshino, W Zhang and J Tu. CFD benchmark tests for indoor environmental problems: Part 3 numerical thermal manikins. *Int. J. Architect. Eng. Tech.* 2015; **2**, 50-75.
[145] K Ito, K Inthavong, T Kurabuchi, T Ueda, T Endo, T Omori, H Ono, S Kato, K Sakai, Y Suwa, H Matsumoto, H Yoshino, W Zhang and J Tu. CFD Benchmark tests for indoor environmental problems: Part 4 air-conditioning airflows, residential kitchen airflows and fire-induced flow. *Int. J. Architect. Eng. Tech.* 2015; **2**, 76-102.
[146] HY Kek, SBM Saupi, H Tan, MHD Othman, BB Nyakuma, PS Goh, WAH Altowayti, A Qaid, NHA Wahab, CH Lee, A Lubis, SL Wong and KY Wong. Ventilation strategies for mitigating airborne infection in healthcare facilities: A review and bibliometric analysis (1993-2022). *Energ. Build.* 2013; **295**, 113323.
[147] S Khan, MK Khan and R Khan. Harnessing intelligent technologies to curb COVID-19 pandemic: Taxonomy and open challenges. *Computing* 2023; **105**, 811-30.
[148] T Khan and S Raza. Exploration of computational aids for effective drug designing and management of viral diseases: A comprehensive review. *Curr. Top. Med. Chem.* 2023; **23**, 1640-63.
[149] ND Khoa, K Kuga, K Inthavong and K Ito. Coupled eulerian wall film-discrete phase model for predicting respiratory droplet generation during a coughing event. *Phys. Fluid.* 2023; **35**, 112103.
[150] J Kim, M Villarreal, S Arya, A Hernandez and A Moreira. Bridging the gap: Exploring bronchopulmonary dysplasia through the lens of biomedical informatics. *J. Clin. Med.* 2024; **13**, 1077.
[151] PK Kirar, SK Soni, PS Kolhe and KC Sahu. An experimental investigation of droplet morphology in swirl flow. *J. Fluid Mech.* 2022; **938**, A6.
[152] J Klinker, MH Selmi, M Avezum and S Jonas. Introducing a navigation algorithm for reducing the spread of diseases in public transport networks. *Stud. Health Tech. Informat.* 2021; **279**, 113-21.
[153] JO Klompmaker, JE Hart, I Holland, MB Sabath, X Wu, F Laden, F Dominici and P James. County-level exposures to greenness and associations with COVID-19 incidence and mortality in the United States. *Environ. Res.* 2021; **199**, 111331.
[154] J Komperda, A Peyvan, D Li, B Kashir, AL Yarin, CM Megaridis, P Mirbod, I Paprotny, LF Cooper, S Rowan, C Stanford and F Mashayek. Computer simulation of the SARS-CoV-2 contamination risk in a large dental clinic. *Phys. Fluid.* 2021; **33**, 033328.
[155] X Kong, C Guo, Z Lin, S Duan, J He, Y Ren and J Ren. Experimental study on the control effect of different ventilation systems on fine particles in a simulated hospital ward. *Sustain. Cities Soc.* 2021; **73**, 103102.
[156] J Krambrich, D Akaberi, J Ling, T Hoffman, L Svensson, M Hagbom and Å Lundkvist. SARS-CoV-2 in hospital indoor environments is predominantly non-infectious. *Virol. J.* 2021; **18**, 109.
[157] K Krishnamurthy and RK Pradhan. Emerging perspectives of synaptic biomarkers in ALS and FTD. *Front. Mol. Neurosci.* 2023; **16**, 1279999.
[158] V Krishnan and AM Kuijpers-Jagtman. *Integrated clinical orthodontics*. Wiley, New Jersey, 2024
[159] OB Kudryashova, EV Muravlev, AA Antonnikova and SS Titov. Propagation of viral bioaerosols indoors. *PLos One* 2021; **16**, e0244983.
[160] K Kuga, P Wargocki and K Ito. Breathing zone and exhaled air re-inhalation rate under transient conditions assessed with a computer-simulated person. *Indoor Air* 2022; **32**, e13003.

[161] S Kumar, R Singh, N Kumari, S Karmakar, M Behera, AJ Siddiqui, VD Rajput, T Minkina, K Bauddh and N Kumar. Current understanding of the influence of environmental factors on SARS-CoV-2 transmission, persistence, and infectivity. *Environ. Sci. Pollut. Res.* 2021; **28**, 6267-88.
[162] AA Kurzhanskiy, F Borrelli and P Varaiya. *Connected and automated vehicles*. Springer, Cham, Germany, 2021, p. 240-50.
[163] VA Lang, T Lundh and M Ortiz-Catalan. Mathematical and computational models for pain: A systematic review. *Pain Med.* 2021; **22**, 2806-17.
[164] B Lee, D Lau, JPM Mogk, M Lee, J Bibliowicz, R Goldstein and A Tessier. Generative design for COVID-19 and future pathogens using stochastic multi-agent simulation. *Sustain. Cities Soc.* 2023; **97**, 104661.
[165] SH Lee, AH Bachman, D Yu, J Lim and BA Ardekani. Predicting progression from mild cognitive impairment to Alzheimer's disease using longitudinal callosal atrophy. *Alzheimer's Dementia* 2016; **2**, 68-74.
[166] E Lepore, PA Benito, CP Ramírez and G Viccione. Indoors ventilation in times of confinement by SARS-CoV-2 epidemic: A comparative approach between Spain and Italy. *Sustain. Cities Soc.* 2021; **72**, 103051.
[167] NHL Leung. Transmissibility and transmission of respiratory viruses. *Nat. Rev. Microbiol.* 2021; **19**, 528-45.
[168] H Li, FY Leong, G Xu, Z Ge, CW Kang and KH Lim. Dispersion of evaporating cough droplets in tropical outdoor environment. *Phys. Fluid.* 2022; **32**, 113301.
[169] H Li, FY Leong, G Xu, CW Kang, KH Lim, BH Tan and CM Loo. Airborne dispersion of droplets during coughing: A physical model of viral transmission. *Sci. Rep.* 2021; **11**, 4617.
[170] J Li, Z Cheng, Y Zhang, N Mao, S Guo, Q Wang, L Zhao and E Long. Evaluation of infection risk for SARS-CoV-2 transmission on university campuses. *Sci. Tech. Built Environ.* 2021; **27**, 1165-80.
[171] M Li, R Zhu, G Li, S Yin, L Zeng, Z Bai, J Chen, B Jiang, L Li and Y Wu. Point-of-care testing for cerebral edema types based on symmetric cancellation near-field coupling phase shift and support vector machine. *BioMedical Eng. Online* 2023; **22**, 80.
[172] S Li. *Computational and experimental simulations in engineering*. Springer, Cham, Germany, 2024.
[173] X Li, Y Qiu, J Zhou and Z Xie. Applications and challenges of machine learning methods in Alzheimer's disease multi-source data analysis. *Curr. Genom.* 2021; **22**, 564-82.
[174] Z Li, X Zhang, T Wu, L Zhu, J Qin and X Yang. Effects of slope and speed of escalator on the dispersion of cough-generated droplets from a passenger. *Phys. Fluid.* 2021; **33**, 041701.
[175] C Lieber, S Melekidis, R Koch and HJ Bauer. Insights into the evaporation characteristics of saliva droplets and aerosols: Levitation experiments and numerical modeling. *J. Aerosol Sci.* 2021; **154**, 105760.
[176] F Liu, Z Luo, Y Li, X Zheng, C Zhang and H Qian. Revisiting physical distancing threshold in indoor environment using infection-risk-based modeling. *Environ. Int.* 2021; **153**, 106542.
[177] J Liu, M Hao, S Chen, Y Yang, J Li, Q Mei, X Bian and K Liu. Numerical evaluation of face masks for prevention of COVID-19 airborne transmission. *Environ. Sci. Pollut. Res.* 2022; **29**, 44939-53.
[178] K Liu, M Allahyari, JS Salinas, N Zgheib and Balachandar. Peering inside a cough or sneeze to explain enhanced airborne transmission under dry weather. *Sci. Rep.* 2021; **11**, 9826.
[179] K Liu, M Allahyari, J Salinas, N Zgheib and S Balachandar. Investigation of theoretical scaling laws using large eddy simulations for airborne spreading of viral contagion from sneezing and coughing. *Phys. Fluid.* 2021; **33**, 63318.
[180] L Liu, J Wei, Y Li and A Ooi. Evaporation and dispersion of respiratory droplets from coughing. *Indoor Air* 2017; **27**, 179-90.
[181] S Liu, Y You, Z Tong and L Zhang. Developing an embedding, koopman and autoencoder technologies-based multi-omics time series predictive model (EKATP) for systems biology research. *Front. Genet.* 2021; **12**, 761629.
[182] X Liu, P Kortoçi, NH Motlagh, P Nurmi and S Tarkoma. A survey of COVID-19 in public transportation: Transmission risk, mitigation and prevention. *Multimodal Transport.* 2022; **1**, 100030.
[183] Y Liu, Y Zhuang, L Yu, Q Li, C Zhao, R Meng, J Zhu and X Guo. A Machine learning framework based on extreme gradient boosting to predict the occurrence and development of infectious diseases in laying hen farms, taking H9N2 as an example. *Animals* 2023; **13**, 1494.
[184] Z Liu, T Li, Z Wang, J Liu, S Huang, BH Min, JY An, KM Kim, S Kim, Y Chen, H Liu, Y Kim, DTW Wong, TJ Huang and YH Xie. Gold nanopyramid arrays for non-invasive surface-enhanced raman spectroscopy-based gastric cancer detection via sEVs. *ACS Appl. Nano Mater.* 2022; **5**, 12506-17.

[185] M Lommel, V Froese, M Sieber, M Jentzsch, T Bierewirtz, Ü Hasirci, T Rese, J Seefeldt, S Schimek, U Kertzscher and CO Paschereit. Novel measurement system for respiratory aerosols and droplets in indoor environments. *Indoor Air* 2021; **31**, 1860-73.
[186] P Lorenzo-Eiroa. *Digital signifiers in an architecture of information*. Routledge, London, 2023.
[187] V Lovec, M Premrov and VŽ Leskovar. Practical impact of the covid-19 pandemic on indoor air quality and thermal comfort in kindergartens. A case study of slovenia. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 9712.
[188] M Lu, G Fu, NB Osman and U Konbr. Green energy harvesting strategies on edge-based urban computing in sustainable internet of things. *Sustain. Cities Soc.* 2021; **75**, 103349.
[189] Y Lu, Y Li, H Zhou, J Lin, Z Zheng, H Xu, B Lin, M Lin and L Liu. Affordable measures to monitor and alarm nosocomial SARS-CoV-2 infection due to poor ventilation. *Indoor Air* 2021; **31**, 1833-42.
[190] E Maggiore, M Tommasini and PM Ossi. Propagation in outdoor environments of aerosol droplets produced by breath and light cough. *Aerosol Sci. Tech.* 2021; **55**, 340-51.
[191] M Marzouk and M Atef. Assessment of indoor air quality in academic buildings using IoT and deep learning. *Sustainability* 2022; **14**, 7015.
[192] C Meaney, M Escobar, R Moineddin, TA Stukel, S Kalia, B Aliarzadeh, T Chen, B O'Neill and M Greiver. Non-negative matrix factorization temporal topic models and clinical text data identify COVID-19 pandemic effects on primary healthcare and community health in Toronto, Canada. *J. Biomed. Informat.* 2022; **128**, 104034.
[193] TH Meen, SD Prior and ADKT Lam. Innovation in design, communication and engineering. *In*: Proceedings of the 2014 3rd International Conference on Innovation, Communication and Engineering, Guizhou, China. 2024.
[194] PP Mehta and V Dhapte-Pawar. *Pulmonary drug delivery systems: Material and technological advances*. Springer, Gateway East, Singapore, 2023.
[195] A Meiss, H Jimeno-Merino, I Poza-Casado, A Llorente-álvarez and MÁ Padilla-Marcos. Indoor air quality in naturally ventilated classrooms. Lessons learned from a case study in a covid-19 scenario. *Sustainability* 2021; **13**, 8446.
[196] A Mikszewski, L Stabile, G Buonanno and L Morawska. The vaccination threshold for SARS-CoV-2 depends on the indoor setting and room ventilation. *BMC Infect. Dis.* 2021; **21**, 1193.
[197] D Mirikar, S Palanivel and V Arumuru. Droplet fate, efficacy of face mask, and transmission of virus-laden droplets inside a conference room. *Phys. Fluid.* 2021; **33**, 065108.
[198] PA Mirzaei, M Moshfeghi, H Motamedi, Y Sheikhnejad and H Bordbar. A simplified tempo-spatial model to predict airborne pathogen release risk in enclosed spaces: An eulerian-lagrangian CFD approach. *Build. Environ.* 2022; **207**, 108428.
[199] R Mittal, R Ni and JH Seo. The flow physics of COVID-19. *J. Fluid Mech.* 2020; **894**, F2.
[200] A Mohammadi, MTU Chowdhury, S Yang and PY Park. Developing levels of pedestrian physical distancing during a pandemic. *Saf. Sci.* 2021; **134**, 105066.
[201] ME Montes and JP Boerman. Graduate student literature review: Social and feeding behavior of group-housed dairy calves in automated milk feeding systems. *J. Dairy Sci.* 2024, https://doi.org/10.3168/jds.2023-23745.
[202] H Moradi, A Al-Hourani, G Concilia, F Khoshmanesh, FR Nezami, S Needham, S Baratchi and K Khoshmanesh. Recent developments in modeling, imaging, and monitoring of cardiovascular diseases using machine learning. *Biophy. Rev.* 2023; **15**, 19-33.
[203] S Moritz, C Gottschick, J Horn, M Popp, S Langer, B Klee, O Purschke, M Gekle, A Ihling, FDL Zimmermann and R Mikolajczyk. The risk of indoor sports and culture events for the transmission of COVID-19. *Nat. Comm.* 2021; **12**, 5096.
[204] H Motamedi, M Shirzadi, Y Tominaga and PA Mirzaei. CFD modeling of airborne pathogen transmission of COVID-19 in confined spaces under different ventilation strategies. *Sustain. Cities Soc.* 2022; **76**, 103397.
[205] AT Murray and S Burtner. Physical distancing as an integral component of pandemic response. *Lett. Spat. Resour. Sci.* 2023; **16**, 8.
[206] S Mursel, N Alter, L Slavit, A Smith, P Bocchini and J Buceta. Estimation of Ebola's spillover infection exposure in Sierra Leone based on sociodemographic and economic factors. *PLos One* 2022; **17**, 8.
[207] J Muthusamy, S Haq, S Akhtar, MA Alzoubi, T Shamim and J Alvarado. Implication of coughing dynamics on safe social distancing in an indoor environment-A numerical perspective. *Build. Environ.* 2021; **206**, 108280.

[208] SS Nayak, A Naidu, SL Sudhakaran, S Vino and G Selvaraj. Prospects of novel and repurposed immunomodulatory drugs against acute respiratory distress syndrome (ARDS) associated with covid-19 disease. *J. Pers. Med.* 2023; **13**, 664.

[209] VS Nori, CA Hane, WH Crown, R Au, WJ Burke, DM Sanghavi and P Bleicher. Machine learning models to predict onset of dementia: A label learning approach. *Alzheimer's Dementia* 2019; **5**, 918-25.

[210] A Núñez and AM García. Effect of the passive natural ventilation on the bioaerosol in a small room. *Build. Environ.* 2022; **207**, 108438.

[211] P Orzelska. *Study of the impact of the quality of communication on the success of projects carried out at higher educational institutions*. UNSW Sydney, Kensington, Australia, 2023.

[212] PS Singh, AK Agarwal, T Gupta and SM Maliyekkal. *New trends in emerging environmental contaminants*. Springer, Gateway East, Singapore 2022.

[213] MJ Page, JE McKenzie, PM Bossuyt, I Boutron, TC Hoffmann, CD Mulrow, L Shamseer, JM Tetzlaff, EA Akl, SE Brennan, R Chou, J Glanville, JM Grimshaw, A Hróbjartsson, MM Lalu, T Li, EW Loder, E Mayo-Wilson, S McDonald, LA McGuinness, ..., D Moher. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* 2021; **372**, n71.

[214] MJ Page, JE McKenzie, PM Bossuyt, I Boutron, TC Hoffmann, CD Mulrow, L Shamseer, JM Tetzlaff, EA Akl, SE Brennan, R Chou, J Glanville, JM Grimshaw, A Hróbjartsson, MM Lalu, T Li, EW Loder, E Mayo-Wilson, S McDonald, LA McGuinness, ..., D Moher. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Syst. Rev.* 2021; **10**, 89.

[215] A Pal, A Gope and A Sengupta. Drying of bio-colloidal sessile droplets: Advances, applications, and perspectives. *Adv. Colloid Interface Sci.* 2023; **314**, 102870.

[216] Y Pan, X Xu, T Luo, S Yang, D Zhou and Y Zeng. A breast cancer prediction model based on a panel from circulating exosomal miRNAs. *BioMed Res. Int.* 2022; **2022**, 5170261.

[217] Y Pan, L Zhang, J Unwin and MJ Skibniewski. Discovering spatial-temporal patterns via complex networks in investigating COVID-19 pandemic in the United States. *Sustain. Cities Soc.* 2022; **77**, 103508.

[218] J Pang, Y Huang, Z Xie, J Li and Z Cai. Collaborative city digital twin for the COVID-19 pandemic: A federated learning solution. *Tsinghua Sci. Tech.* 2021; **26**, 759-71.

[219] S Paprocki, M Qassem and PA Kyriacou. Review of ethanol intoxication sensing technologies and techniques. *Sensors* 2022; **22**, 6819.

[220] JH Park, HE Cho, JH Kim, MM Wall, Y Stern, H Lim, S Yoo, HS Kim and J Cha. Machine learning prediction of incidence of Alzheimer's disease using large-scale administrative health data. *NPJ Digital Med.* 2020; **3**, 46.

[221] S Park, Y Choi, D Song and EK Kim. Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building. *Sci. Total Environ.* 2021; **789**, 147764.

[222] R Patil, R Dave, H Patel, VM Shah, D Chakrabarti and U Bhatia. Assessing the interplay between travel patterns and SARS-CoV-2 outbreak in realistic urban setting. *Appl. Network Sci.* 2021; **6**, 4.

[223] A Paul, JK Bhattacharjee, A Pal and S Chakraborty. Emergence of universality in the transmission dynamics of COVID-19. *Sci. Rep.* 2021; **11**, 18891.

[224] A Paul, M Bhattacharjee and R Dahiya. Solid-State Sensors. *Solid-State Sensors*. Wiley, New Jersey 2023.

[225] AB Payedimarri, D Concina, L Portinale, M Canonico, D Seys, K Vanhaecht and M Panella. Prediction models for public health containment measures on covid-19 using artificial intelligence and machine learning: A systematic review. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 4499.

[226] DD Pednekar, MA Liguori, CNH Marques, T Zhang, N Zhang, Z Zhou, K Amoako and H Gu. From static to dynamic: A review on the role of mucus heterogeneity in particle and microbial transport. *ACS Biomater. Sci. Eng.* 2022; **8**, 2825-48.

[227] PHP Gregorio, AW Mariani, JMLT Brito, BJM Santos and PM Pêgo-Fernandes. Indoor air quality and environmental sampling as support tools to detect SARS-CoV-2 in the healthcare setting. *J. Occupational Environ. Med.* 2021; **63**, 956-62.

[228] S Peng, Q Chen and E Liu. The role of computational fluid dynamics tools on investigation of pathogen transmission: Prevention and control. *Sci. Total Environ.* 2020; **746**, 142090.

[229] Y Peng and Y Chen. Integrative soft computing approaches for optimizing thermal energy performance in residential buildings. *PLos One* 2023; **18**, e0290719.

[230] N Perra. Non-pharmaceutical interventions during the COVID-19 pandemic: A review. *Phys. Rep.* 2021; **913**, 1-52.

[231] JR Petrella, W Hao, A Rao, PM Doraiswamy and S Li. Computational causal modeling of the dynamic biomarker cascade in Alzheimer's disease. *Comput. Math. Methods Med.* 2019; **2019**, 6216530.
[232] MC Pietrogrande, L Casari, G Demaria and M Russo. Indoor air quality in domestic environments during periods close to italian covid-19 lockdown. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 4060.
[233] L Predescu and D Dunea. Performance evaluation of particulate matter and indoor microclimate monitors in university classrooms under covid-19 restrictions. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 7363.
[234] O Puhach, K Adea, N Hulo, P Sattonnet, C Genecand, A Iten, F Jacquérioz, L Kaiser, P Vetter, I Eckerle and B Meyer. Infectious viral load in unvaccinated and vaccinated individuals infected with ancestral, Delta or Omicron SARS-CoV-2. *Nat. Med.* 2022; **28**, 1491-500.
[235] N Puttaswamy, V Sreekanth, A Pillarisetti, AR Upadhya, S Saidam, B Veerappan, K Mukhopadhyay, S Sambandam, R Sutaria and K Balakrishnan. Indoor and ambient air pollution in Chennai, India during COVID-19 lockdown: An affordable sensors study. *Aerosol Air Qual. Res.* 2022; **22**, 210170.
[236] Q Rafique, A Rehman, MS Afghan, HM Ahmad, I Zafar, K Fayyaz, Q Ain, RA Rayan, KM Al-Aidarous, S Rashid, G Mushtaq and R Sharma. Reviewing methods of deep learning for diagnosing COVID-19, its variants and synergistic medicine combinations. *Comput. Biol. Med.* 2023; **163**, 107191.
[237] KS Raines, S Doniach and G Bhanot. The transmission of SARS-CoV-2 is likely comodulated by temperature and by relative humidity. *PLos One* 2021; **16**, e0255212.
[238] AS Ramirez-Mata, D Ostrov, M Salemi, S Marini and BR Magalis. Machine learning prediction and phyloanatomic modeling of viral neuroadaptive signatures in the macaque model of hiv-mediated neuropathology. *Microbiol. Spectrum* 2023; **11**, e0308622.
[239] M Razavi, ZA Butt, H Chen and Z Tan. In situ measurement of airborne particle concentration in a real dental office: Implications for disease transmission. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 8955.
[240] SA Rezaeieh, A Darvazehban, AS Janani and AM Abbosh. Electromagnetic torso scanning: A review of devices, algorithms, and systems. *Biosensors* 2021; **11**, 135.
[241] MJ Risbeck, MZ Bazant, Z Jiang, YM Lee, KH Drees and JD Douglas. Modeling and multiobjective optimization of indoor airborne disease transmission risk and associated energy consumption for building HVAC systems. *Energ. Build.* 2021; **253**, 111497.
[242] K Ritchie, CW Ritchie, K Jaffe, I Skoog and N Scarmeas. Is late-onset Alzheimer's disease really a disease of midlife? *Alzheimer's Dementia* 2015; **1**, 122-30.
[243] E Rivas, JL Santiago, F Martín and A Martilli. Impact of natural ventilation on exposure to SARS-CoV 2 in indoor/semi-indoor terraces using CO_2 concentrations as a proxy. *J. Build. Eng.* 2022; **46**, 103725.
[244] JF Robinson, IRD Anda, FJ Moore, JP Reid, RP Sear and CP Royall. Efficacy of face coverings in reducing transmission of COVID-19: Calculations based on models of droplet capture. *Phys. Fluid.* 2021; **33**, 43112.
[245] T Rocha-Santos, MF Costa and C Mouneyrac. *Handbook of microplastics in the environment*. Springer, Cham, Germany, 2022.
[246] D Rodríguez, IR Urbieta, Á Velasco, MÁ Campano-Laborda and E Jiménez. Assessment of indoor air quality and risk of COVID-19 infection in Spanish secondary school and university classrooms. *Build. Environ.* 2022; **226**, 109717.
[247] M Rodríguez, ML Palop, S Seseña and A Rodríguez. Are the portable air cleaners (PAC) really effective to terminate airborne SARS-CoV-2? *Sci. Total Environ.* 2021; **785**, 147300.
[248] T Roh, A Moreno-Rangel, J Baek, A Obeng, NT Hasan and G Carrillo. Indoor air quality and health outcomes in employees working from home during the covid-19 pandemic: A pilot study. *Atmosphere* 2021; **12**, 1665.
[249] M Rohini and D Surendran. Classification of neurodegenerative disease stages using ensemble machine learning classifiers. *Proc. Comput. Sci.* 2019; **165**, 66-73.
[250] DA Rothamer, S Sanders, D Reindl and TH Bertram. Strategies to minimize SARS-CoV-2 transmission in classroom settings: Combined impacts of ventilation and mask effective filtration efficiency. *Sci. Tech. Built Environ.* 2021; **27**, 1181-203.
[251] S Roy, A Cherevko, S Chakraborty, N Ghosh and P Ghosh. Leveraging network science for social distancing to curb pandemic spread. *IEEE Access* 2021; **9**, 26196-207.
[252] P Saikia, D Rakshit, R Narayanaswamy, F Wang and Udayraj. Energy performance and indoor airflow analysis of a healthcare ward designed with resource conservation objectives. *J. Build. Eng.* 2021; **44**, 103296.

[253] MY Salman and H Hasar. Review on environmental aspects in smart city concept: Water, waste, air pollution and transportation smart applications using IoT techniques. *Sustain. Cities Soc.*2023; **94**, 104567.
[254] AR Sarhan, P Naser and J Naser. COVID-19 aerodynamic evaluation of social distancing in indoor environments, a numerical study. *J. Environ. Health Sci. Eng.* 2021; **19**, 1969-78.
[255] G Saxena, M Sharma, F Fatima, P Bajpai and S Akhtar. *In silico molecular modelling: Key technologies in the drug discovery process to combat multidrug resistance*. *In*: I Ahmad, S Ahmad and K Rumbaugh. (Eds.). Antibacterial Drug Discovery to Combat MDR. Springer, Gateway East, Singapore, 2019, p. 213-38.
[256] W Schade, V Reimer, M Seipenbusch and U Willer. Experimental investigation of aerosol and CO_2 dispersion for evaluation of covid-19 infection risk in a concert hall. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 3037.
[257] L Schibuola and C Tambani. High energy efficiency ventilation to limit COVID-19 contagion in school environments. *Energ. Build.* 2021; **240**, 110882.
[258] L Schibuola and C Tambani. Performance comparison of heat recovery systems to reduce viral contagion in indoor environments. *Appl. Therm. Eng.* 2021; **190**, 116843.
[259] D Selvakarthi, D Sivabalaselvamani, S Ashwath, APA Kalaivanan, K Manikandan and C Pradeep. Experimental analysis using deep learning techniques for safety and riskless transport-a sustainable mobility environment for post covid-19. *In*: Proceedings of the 2021 6th International Conference on Inventive Computation Technologies, Coimbatore, India. 2021.
[260] JR Sempionatto, JA Lasalde-Ramírez, K Mahato, J Wang and W Gao. Wearable chemical sensors for biomarker discovery in the omics era. *Nat. Rev. Chem.* 2022; **6**, 899-915.
[261] N Sen and KK Singh. When the doorbell rings in COVID-19 times: Numerical insights into some possible scenarios. *Phys. Fluid.* 2021; **33**, 045128.
[262] H Sha, X Zhang and D Qi. Optimal control of high-rise building mechanical ventilation system for achieving low risk of COVID-19 transmission and ventilative cooling. *Sustain. Cities Soc.* 2021; **74**, 103256.
[263] Y Shahzad, SAA Rizvi, AM Yousaf and T Hussain. *Drug delivery using nanomaterials*. CRC Press, Florida, 2022.
[264] Y Shang, J Dong, L Tian, F He and J Tu. An improved numerical model for epidemic transmission and infection risks assessment in indoor environment. *J. Aerosol Sci.* 2022; **162**, 105943.
[265] A Sharifi, AR Khavarian-Garmsir, Z Allam and A Asadzadeh. Progress and prospects in planning: A bibliometric review of literature in Urban Studies and Regional and Urban Planning, 1956-2022. *Prog. Plann.* 2023; **173**, 100740.
[266] R Sharma, R Kannojiya, N Garg and SS Gautam. *Advances in engineering design*. Springer, Gateway East, Singapore, 2019.
[267] J Shen, M Kong, B Dong, MJ Birnkrant and J Zhang. A systematic approach to estimating the effectiveness of multi-scale IAQ strategies for reducing the risk of airborne infection of SARS-CoV-2. *Build. Environ.* 2021; **200**, 107926.
[268] J Sheng, B Wang, Q Zhang and M Yu. Connectivity and variability of related cognitive subregions lead to different stages of progression toward Alzheimer's disease. *Heliyon* 2022; **8**, e08827.
[269] F Shi, C Huang, Y Ren, C Deng, N Sun and X Shen. Multiscale element-doped nanowire array-coupled machine learning reveals metabolic fingerprints of nonreversible liver diseases. *Anal. Chem.* 2022; **94**, 16204-12.
[270] Y Shi, C Zhang, S Pan, Y Chen, X Miao, G He, Y Wu, H Ye, C Weng, H Zhang, W Zhou, X Yang, C Liang, D Chen, L Hong and F Su. The diagnosis of tuberculous meningitis: Advancements in new technologies and machine learning algorithms. *Front. Microbiol.* 2023; **14**, 1290746.
[271] N Shinohara, K Tatsu, N Kagi, H Kim, J Sakaguchi, I Ogura, Y Murashima, H Sakurai and W Naito. Air exchange rates and advection-diffusion of CO_2 and aerosols in a route bus for evaluation of infection risk. *Indoor Air* 2022; **32**, e13019.
[272] M Shoaib, R Tabassum, KS Nisar and MAZ Raja. A framework for the analysis of skin sores disease using evolutionary intelligent computing approach. *Comput. Methods Biomech. Biomed. Eng.* 2024, https://doi.org/10.1080/10255842.2024.2326888.
[273] P Shrestha, JW DeGraw, M Zhang and X Liu. Multizonal modeling of SARS-CoV-2 aerosol dispersion in a virtual office building. *Build. Environ.* 2021; **206**, 108347.
[274] SJRD Silva, SCD Lima, RCD Silva, A Kohl and L Pena. Viral load in covid-19 patients: Implications for prognosis and vaccine efficacy in the context of emerging SARS-CoV-2 variants. *Front. Med.* 2022; **8**, 836826.

[275] BC Singer, H Zhao, CV Preble, WW Delp, J Pantelic, MD Sohn and TW Kirchstetter. Measured influence of overhead HVAC on exposure to airborne contaminants from simulated speaking in a meeting and a classroom. *Indoor Air* 2022; **32**, e12917.
[276] P Singh, CM Hussain and M Sillanpää. *Innovative bio-based technologies for environmental remediation*. CRC Press, Florida, 2022.
[277] SK Singh, A Kumar, RB Singh, P Ghosh and NG Bajad. Recent applications of bioinformatics in target identification and drug discovery for Alzheimer's disease. *Curr. Top. Med. Chem.* 2022; **22**, 2153-75.
[278] A Sircar, G Tripathi, N Bist, KA Shakil and M Sathiyanarayanan. *Emerging technologies for sustainable and smart energy*. CRC Press, Florida, 2022.
[279] K Skianis, G Nikolentzos, B Gallix, R Thiebaut and G Exarchakis. Predicting covid-19 positivity and hospitalization with multi-scale graph neural networks. *Sci. Rep.* 2023; **13**, 5235.
[280] K Skolariki, TP Exarchos and P Vlamos. Computational models for biomarker discovery. *Adv. Exp. Med. Biol.* 2023; **1424**, 289-95.
[281] K Skolariki, GM Terrera and SO Danso. Predictive models for mild cognitive impairment to Alzheimer's disease conversion. *Neural Regener. Res.* 2021; **16**, 1766-7.
[282] S Srivastava, X Zhao, A Manay and Q Chen. Effective ventilation and air disinfection system for reducing coronavirus disease 2019 (COVID-19) infection risk in office buildings. *Sustain. Cities Soc.* 2021; **75**, 103408.
[283] L Stabile, A Pacitto, A Mikszewski, L Morawska and G Buonanno. Ventilation procedures to minimize the airborne transmission of viruses in classrooms. *Build. Environ.* 2021; **202**, 108042.
[284] W Strielkowski, S Zenchenko, A Tarasova and Y Radyukova. Management of smart and sustainable cities in the post-covid-19 era: Lessons and implications. *Sustainability* 2022; **14**, 7267.
[285] AF Subahi. A model transformation approach for detecting distancing violations in weighted graphs. *Comput. Syst. Sci. Eng.* 2021; **36**, 13-39.
[286] Y Sui, H Yu, C Zhang, Y Chen, C Jiang and L Li. Deep brain-machine interfaces: Sensing and modulating the human deep brain. *Natl. Sci. Rev.* 2022; **9**, nwac212.
[287] S Sundar, C Battistoni, R McNulty, F Morales, J Gorky, H Foley and P Dhurjati. An agent-based model to investigate microbial initiation of Alzheimer's via the olfactory system. *Theor. Biol. Med. Modell.* 2020; **17**, 5.
[288] S Suppadungsuk, C Thongprayoon, J Miao, P Krisanapan, F Qureshi, K Kashani and W Cheungpasitporn. Exploring the potential of chatbots in critical care nephrology. *Medicines* 2023; **10**, 58.
[289] S Taheri and A Razban. Learning-based CO2 concentration prediction: Application to indoor air quality control using demand-controlled ventilation. *Build. Environ.* 2021; **205**, 108164.
[290] F Tahmasebi, Y Wang, E Cooper, DG Shimizu, S Stamp and D Mumovic. Window operation behaviour and indoor air quality during lockdown: A monitoring-based simulation-assisted study in London. *Build. Serv. Eng. Res. Tech.* 2022; **43**, 5-21.
[291] HR Tamaddon Jahromi, I Sazonov, J Jones, A Coccarelli, S Rolland, NK Chakshu, H Thomas and P Nithiarasu. Predicting the airborne microbial transmission via human breath particles using a gated recurrent units neural network. *Int. J. Numer. Methods Heat Fluid Flow* 2022; **32**, 2964-81.
[292] T Temel, CM Vernon, B Ulas, PG Jason, Z Xuandong, DK Anil, F Nicholas, GR Joseph, SK Zarine, PD Peter, S Benjamin, Z Atif, XL Karen, WM Ashley, M Campbell-Thompson, CL Darwin, FL Evan, FE Christopher, HA Phil, PJ Stephen, ..., Y Dhiraj. Design and rationale for the use of magnetic resonance imaging biomarkers to predict diabetes after acute pancreatitis in the D iabetes RE lated to a cute pancreatitis and its m echanisms study: From the type 1 diabetes in acute pancreatitis consortium. *Pancreas* 2022; **51**, 586-92.
[293] O Toker. *Computational complexity in robustness analysis and design*. *In*: J Baillieul and T Samad (Eds.). Encyclopedia of Systems and Control. Springer, Cham, Germany, 2021.
[294] J Tryner, M Phillips, C Quinn, G Neymark, A Wilson, SH Jathar, E Carter and J Volckens. Design and testing of a low-cost sensor and sampling platform for indoor air quality. *Build. Environ.* 2021; **206**, 108398.
[295] A Tuladhar, JA Moore, Z Ismail and ND Forkert. Modeling neurodegeneration *in silico* with deep learning. *Front. Neuroinformatics* 2021; **15**, 748370.
[296] I Tzoutzas, HC Maltezou, N Barmparesos, P Tasios, C Efthymiou, MN Assimakopoulos, M Tseroni, R Vorou, F Tzermpos, M Antoniadou, V Panis and P Madianos. Indoor air quality evaluation using mechanical ventilation and portable air purifiers in an academic dentistry clinic during the covid-19 pandemic in greece. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 8886.

[297] VV Toi, TH Nguyen, VB Long and HTT Huong. *8th international conference on the development of biomedical engineering in Vietnam*. Springer, Cham, Germany, 2022.
[298] A Vashishat, P Patel, GD Gupta and BD Kurmi. Alternatives of animal models for biomedical research: A comprehensive review of modern approaches. *Stem Cell Rev. Rep.* 2024; **20**, 881-99.
[299] CC Vassella, J Koch, A Henzi, A Jordan, R Waeber, R Iannaccone and R Charrière. From spontaneous to strategic natural window ventilation: Improving indoor air quality in Swiss schools. *Int. J. Hyg. Environ. Health* 2021; **234**, 113746.
[300] D Vernez, S Schwarz, JJ Sauvain, C Petignat and G Suarez. Probable aerosol transmission of SARS-CoV-2 in a poorly ventilated courtroom. *Indoor Air* 2021; **31**, 1776-85.
[301] C Viegas, R Pimenta, M Dias, B Gomes, M Brito, LA Caetano, E Carolino and AQ Gomes. Microbiological contamination assessment in higher education institutes. *Atmosphere* 2021; **12**, 1079.
[302] F Vigo, A Tozzi, M Disler, A Gisi, V Kavvadias and T Kavvadias. Vibrational spectroscopy in urine samples as a medical tool: Review and overview on the current State-of-the-Art. *Diagnostics* 2023; **13**, 27.
[303] F Villanueva, A Notario, B Cabañas, P Martín, S Salgado and MF Gabriel. Assessment of CO_2 and aerosol ($PM_{2.5}$, PM_{10}, UFP) concentrations during the reopening of schools in the COVID-19 pandemic: The case of a metropolitan area in Central-Southern Spain. *Environ. Res.* 2021; **197**, 111092.
[304] A Vlachokostas, CA Burns, TI Salsbury, RC Daniel, DP James, JE Flaherty, N Wang, RM Underhill, G Kulkarni and LF Pease. Experimental evaluation of respiratory droplet spread to rooms connected by a central ventilation system. *Indoor Air* 2022; **32**, e12940.
[305] M Vosoughi, C Karami, A Dargahi, F Jeddi, KM Jalali, A Hadisi, SB Haghighi, HP Dogahe, Z Noorimotlagh and SA Mirzaee. Investigation of SARS-CoV-2 in hospital indoor air of COVID-19 patients' ward with impinger method. *Environ. Sci. Pollut. Res.* 2021; **28**, 50480-8.
[306] CVM Vouriot, HC Burridge, CJ Noakes and PF Linden. Seasonal variation in airborne infection risk in schools due to changes in ventilation inferred from monitored carbon dioxide. *Indoor Air* 2021; **31**, 1154-63.
[307] B Wang, H Wu and XF Wan. Transport and fate of human expiratory droplets-A modeling approach. *Phys. Fluid.* 2020; **32**, 83307.
[308] C Wang, SJ Yoo and K Ito. Does detailed hygrothermal transport analysis in respiratory tract affect skin surface temperature distributions by thermoregulation model? *Adv. Build. Energ. Res.* 2020; **14**, 450-70.
[309] H Wang, T Fu, Y Du, W Gao, K Huang, Z Liu, P Chandak, S Liu, PV Katwyk, A Deac, A Anandkumar, K Bergen, CP Gomes, S Ho, P Kohli, J Lasenby, J Leskovec, TY Liu, A Manrai, D Marks, …, M Zitnik. Scientific discovery in the age of artificial intelligence. *Nature* 2023; **620**, 47-60.
[310] LL Wang, H Ge, ZJ Zhai, D Qi, M Ouf, C Sun and D Wang. *Proceedings of the 5th international conference on building energy and environment*. Springer, Gateway East, Singapore, 2023.
[311] L Wang, SA Romo, E Sanico, HD Costa, T Lin, N Rabchevsky, M Kern, S Zhu and J Srebric. A wearable micro air cleaner for occupant-oriented indoor environmental controls. *Build. Environ.* 2023; **243**, 110635.
[312] L Wang, X Rong and L Mu. The spatial pattern and dynamic evolution of basic public service level in Beijing-Tianjin-Hebei region from the perspective of COVID-19. *Eng. Constr. Archit. Manage.* 2023; **30**, 3438-60.
[313] N Wang, Y Zhang, W Wang, Z Ye, H Chen, G Hu and D Ouyang. How can machine learning and multiscale modeling benefit ocular drug development? *Adv. Drug Delivery Rev.* 2023; **196**, 114772.
[314] S Wang and X Huang. A review on higher education of fire safety in China. *Fire Tech.* 2023; **60**, 757-816.
[315] T Wang, RG Qiu and M Yu. Predictive modeling of the progression of Alzheimer's disease with recurrent neural networks. *Sci. Rep.* 2018; **8**, 9161.
[316] KKL Wong, W Xu, M Ayoub, YL Fu, H Xu, R Shi, M Zhang, F Su, Z Huang and W Chen. Brain image segmentation of the corpus callosum by combining Bi-Directional convolutional LSTM and U-Net using multi-slice CT and MRI. *Comput. Methods Programs Biomed.* 2023; **238**, 107602.
[317] X Wu, Q Zhou, L Mu and X Hu. Machine learning in the identification, prediction and exploration of environmental toxicology: Challenges and perspectives. *J. Hazard. Mater.* 2022; **438**, 129487.
[318] H Xiao, S Ali, Z Zhang, MS Sarfraz, F Zhang and M Faisal. Big data, extracting insights, comprehension, and analytics in cardiology: An overview. *J. Healthcare Eng.* 2021; **2021**, 1-14.

[319] J Xie, H Li, S Su, J Cheng, Q Cai, H Tan, L Zu, X Qu and H Han. Quantitative analysis of molecular transport in the extracellular space using physics-informed neural network. *Comput. Biol. Med.* 2024; **171**, 108133.
[320] G Xin, J Niu, Q Tian, Y Fu, L Chen, T Yi, K Tian, X Sun, N Wang, J Wang, H Zhang and L Wang. Identification of potential immune-related hub genes in Parkinson's disease based on machine learning and development and validation of a diagnostic classification model. *PLos One* 2023; **18**, e0294984.
[321] W Xu, L Chen, G Cai, M Gao, Y Chen, J Pu, X Chen, N Liu, Q Ye and K Qian. Diagnosis of Parkinson's disease via the metabolic fingerprint in saliva by deep learning. *Small Methods* 2023; **7**, 2300285.
[322] W Xu, L Xiang, D Proverbs and S Xiong. The influence of covid-19 on community disaster resilience. *Int. J. Environ. Res. Publ. Health* 2021; **18**, 88.
[323] M Yamakawa, A Kitagawa, K Ogura, YM Chung and M Kim. Computational investigation of prolonged airborne dispersion of novel coronavirus-laden droplets. *J. Aerosol Sci.* 2021; **155**, 105769.
[324] L Yang, M Iwami, Y Chen, M Wu and KHV Dam. A systematic review of urban design and computer modelling methods to support smart city development in a post-covid era. *Lect. Notes Civil Eng.* 2022; **211**, 1234-46.
[325] L Yang, M Iwami, Y Chen, M Wu and KHV Dam. Computational decision–support tools for urban design to improve resilience against COVID-19 and other infectious diseases: A systematic review. *Prog. Plann.* 2023; **168**, 100657.
[326] Y Yang, Y Li, K Kral, N Hupert and T Dogan. Urban design attributes and resilience: Covid-19 evidence from New York City. *Build. Cities* 2021; **2**, 618-36.
[327] Y Yang, Y Lu, L Yang, Z Gou and Y Liu. Urban greenery cushions the decrease in leisure-time physical activity during the covid-19 pandemic: A natural experimental study. *Urban For. Urban Greening* 2021; **62**, 127136.