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Research article

Effect of microplastics deposition on human lung airways: A review with computational benefits and challenges

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ABSTRACT

Microplastics have become omnipresent in the environment, including the air we inhale, the water we consume, and the food we eat. Despite limited research, the accumulation of microplastics within the human respiratory system has garnered considerable interest because of its potential implications for health. This review offers a comprehensive examination of the impacts stemming from the accumulation of microplastics on human lung airways and explores the computational benefits and challenges associated with studying this phenomenon. The existence of microplastics in the respiratory system can lead to a range of adverse effects. Research has indicated that microplastics can induce inflammation, oxidative stress, and impaired lung function. Furthermore, the small size of microplastics allows them to penetrate deep into the lungs, reaching the alveoli, where gas exchange takes place. This raises concerns about long-term health consequences, such as the development of respiratory diseases and the potential for translocation to other organs. Computational approaches have been instrumental in understanding the impact of microplastic deposition on human lung airways. Computational models and simulations enable the investigation of particle dynamics, deposition patterns, and interaction mechanisms at various levels of complexity. However, studying microplastics in the lung airways using computational methods presents several challenges. The complex anatomy and physiological processes of the respiratory system require accurate representation in computational models. Obtaining relevant data for model validation and parameterization remains a significant hurdle. Additionally, the diverse nature of microplastics, including variations in size, shape, and chemical composition, poses challenges in capturing their full range of behaviours and potential toxicological effects.

1. Introduction

Microplastics, which are minuscule plastic particles, have become widespread in the surroundings, and their prospective repercussions on human well-being remain unclear. These tiny particles are found everywhere, including in drinking water, salt, seafood, and even the atmosphere. Individuals may unknowingly consume anywhere from a few tens to millions of microplastic particles every day, and in severe cases, the amount of microplastics consumed in a year can be equivalent to the weight of a small card. Regulators are taking initial steps to evaluate the prospective peril associated with the exposure of humans to microplastics and their potential impact on health. But unfortunately, the problem is expected to worsen as plastics in landfills and the environment break down into even

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smaller fragments, making it increasingly difficult to remove or reduce them. Microplastics pose a growing concern as they are ubiquitous in air, drinking water, salt, and seafood, and they can cause irritation if small enough to enter cells or tissues. Larger microplastics pose an even greater risk due to their chemical toxicity, which stems from the presence of hazardous substances that interfere with endocrine systems. However, scientists are only beginning to study how quickly these chemicals leave plastic particles and how fast the particles move through our bodies.

The term "microplastics" has become widely recognized on a global scale over the past ten years, even though it was first introduced by Professor Richard Thompson in 2004 [1]. As defined by many researchers, microplastics are small plastic pieces usually measuring less than 5 mm in length but larger than 0.1 μm. They can have various shapes, including irregular, spherical, and fibrous [2–4]. Scientists also determined that plastic particles exceeding 25 mm in size, spanning from 5 to 25 mm, 1–5 mm, and 1 nm to 1 μm, were classified as macroplastics, mesoplastics, microplastics, and nanoplastics, respectively [5,6]. One of the most concerning aspects of microplastics is their non-biodegradable nature, which means that they endure within the environment for a prolonged duration. The non-biodegradability of microplastics is a fundamental issue that exacerbates plastic pollution.

Microplastics constitute only a small subset of plastic materials, which can refer to any physical object made of plastic compounds or polymers [7]. Regardless of their size or name, all plastic materials possess their inherent properties. For example, a plastic drinking glass and its broken pieces are both forms of plastic. When plastic items break down, sunlight can cause changes to the molecular structure of the material, making it more fragile, and leading to the development of microplastics [8]. The primary raw materials used in plastic production are ethylene and propylene, which are obtained from oil and gas sources [9].

Commencing from the 1950s, the fabrication of plastics has undergone exponential proliferation. As of 2015, approximately 6.3 billion metric tons of plastic waste had been generated with a significant proportion (roughly 79 %) either deposited in landfills or dispersed within the environment. Moreover, if the present trajectory persists, it is anticipated that by 2050, an accumulation of nearly 12 billion metric tons of plastic waste will have materialized [10]. Moreover, plastic production releases billions of tons of greenhouse gases, contributing to the overall increase of these gases in the atmosphere [11]. Australia, for instance, produces around 3 million tons of plastic materials yearly, but only 12 % of this is recycled, with the remaining portion being thrown away after a single use [12]. This generates microplastics, which can have severe implications for human health. These tiny particles can be absorbed by cells, tissues,

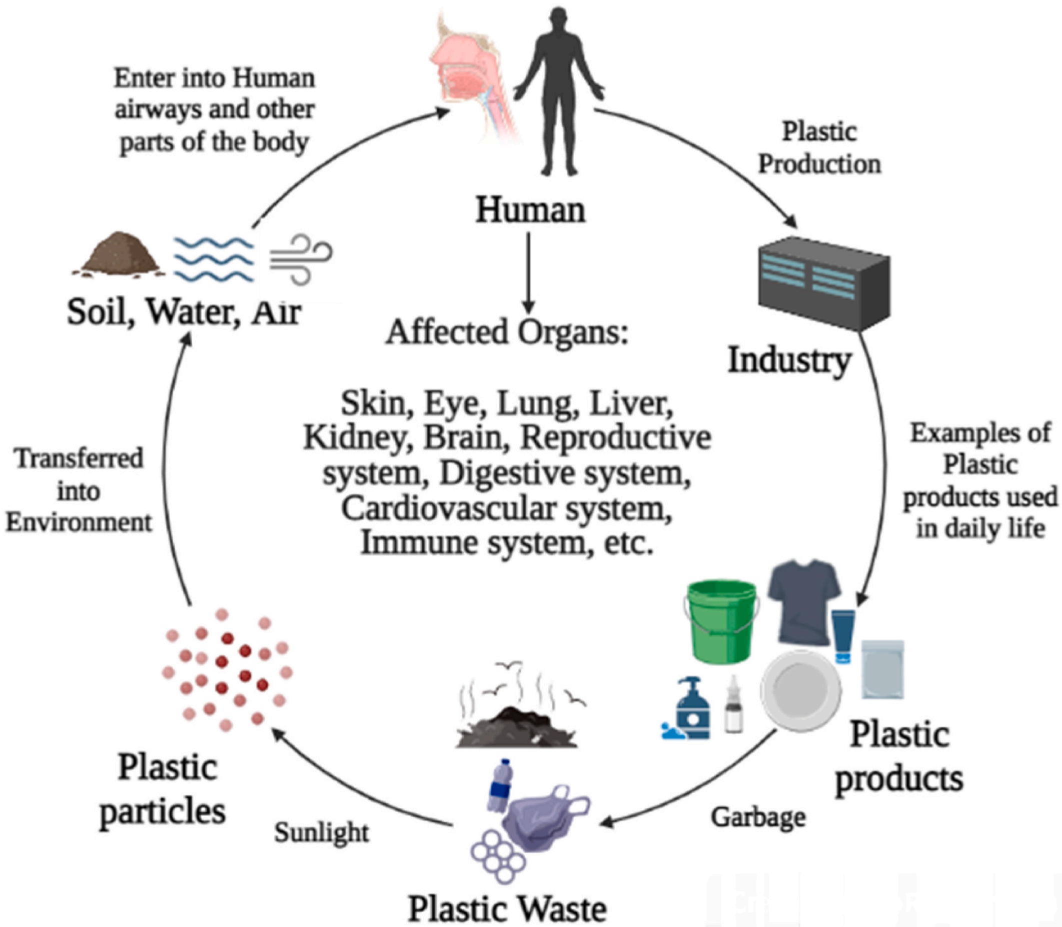

Fig. 1. Diagram of microplastic contamination: Comprehending routes and hazards to human well-being.

and organs, causing tissue inflammation, allergic reactions, loss of appetite, liver and gastrointestinal problems, lung issues, and cellular damage. Details are presented in Fig. 1 [13–16].

In 2020, a study examined the occurrence of heavy metals within microplastics located in the Pearl River [17]. The researchers analyzed samples of the microplastics and found the existence of several heavy metals, including arsenic (As), zinc (Zn), cadmium (Cd), nickel (Ni), iron (Fe), manganese (Mn), and copper (Cu). The study also revealed that the highest concentrations of iron, zinc, and manganese were detected in the microplastics. Tarasco et al. [18] observed that continuous exposure to microplastics not only endangers the growth, reproductive abilities, and bone health of Zebrafish but also results in generational impacts. It is a widely accepted truth that microplastics have been found in a diverse array of aquatic organisms in both marine and freshwater environments [19,20] and also found in sea salt [21,22]. These findings indicate that the existence of metals in microplastics and the presence of microplastics in water can cause damage to marine life and generate a plausible hazard to human health through the intricate dynamics of the food chain.

In a series of interconnected studies, microplastics have been discovered in various unexpected places, shedding light on the pervasive nature of this environmental concern. Researchers have identified microplastics within placental tissue [23,24]. Moreover, for the first time, the presence of microplastics has been confirmed in human blood [25]. It has been unveiled that these microplastics can navigate through the bloodstream, ultimately distributing themselves throughout the human body. Also, microplastics have been found to infiltrate our daily consumption habits, such as tea consumption [26]. Many tea bags, despite their natural fiber composition, employ plastic for packaging, which can release microplastics when subjected to high temperatures, thus becoming an unintended source of ingestion. In a parallel study, researchers uncovered hazardous levels of microplastics in various sugar brands [27]. Equally concerning is the discovery of microplastics in human breast milk, highlighting the potential transfer of these contaminants to infants [28]. The reach of microplastics extends even further, affecting the human reproductive system. Research has revealed that approximately 40% of men's semen contains harmful substances, including microplastics, which are known to accumulate in the seminal vesicles [29]. Additionally, microplastics have been detected in the human heart, indicating their ability to infiltrate vital organs [30]. Scientists have even identified microplastics in the atmosphere, including clouds [31]. These airborne microplastics reach the upper atmosphere, where they are exposed to harmful ultraviolet radiation from the sun. As a result, these particles become part of the atmospheric makeup, contributing to the production of toxic greenhouse gases.

As discussed earlier, microplastics are small plastic particles that are found in the environment, including in the air, soil, and water as shown in Fig. 1. These tiny particles can be easily inhaled by humans, which allows them to enter our bodies and potentially cause harm. In fact, microplastics have been shown to accumulate in different organs of the human body, particularly the lungs. When microplastics enter the lungs, they can damage the lung tissue and cells, and may even have an impact on our immune systems. For individuals with pre-existing pulmonary conditions, such as asthma or chronic obstructive pulmonary disease (COPD), exposure to microplastics can be particularly concerning. This is because these individuals may be more vulnerable to inflammation in the lungs, which can exacerbate their existing condition and lead to further health complications. Additionally, most plastics are not recyclable, meaning that they persist in the environment for a long period of time. Since microplastics are easily inhaled and ingested by both humans and wildlife, this creates a serious concern for our environment and public health.

1.1. *Primary source of microplastics*

Microplastics are generated from a range of sources, but there are four primary areas that significantly contribute to their proliferation: cosmetics, textiles, single-use plastics, and tires. These four key areas will be further discussed below.

1.2. *Cosmetics*

Every year, around 3800 tons of microplastics are introduced into the environment solely from the daily use of cosmetics in continental Europe [32]. It is challenging to estimate how much microplastics are released from cosmetics in other countries or the world as a whole, but it is undoubtedly a substantial amount. Sometimes, a single cosmetic product contains synthetic or plastic polymers, which can make up to nearly 90 % of its ingredients [33]. When these products are used and washed off in our bathrooms or toilets, the small particles or components are carried into the sewage treatment system through the drains, rivers, and ponds. In an ideal system, the wastewater should be directed to a treatment plant before being released back into the environment. Otherwise, it will be directly added to rivers, ponds, channels, or reservoirs, along with the plastic materials from cosmetic products. When the water is treated in a plant, the leftover residue is often mixed with soil.

Cosmetic manufacturers have used alternative ways to describe the contents of their products, avoiding the use of the term "plastic." Rather than using that word, they opt for phrases like "water-soluble polymers," "liquid polymers," "biodegradable polymers," and other similar terms. By using these alternative descriptions, they are able to present their products in a positive light, emphasizing their eco-friendly nature and appealing to consumers who prioritize sustainability in their purchasing decisions. Polyvinyl alcohol is the most widely used water-soluble polymer in the cosmetics industry, with an annual consumption of 650,000 tons [34,35]. However, these polymers do not fully dissolve in water and can still release plastic particles into the environment, especially at higher concentrations or under certain conditions like humidity, microorganisms, temperature, and time. Even with water treatment, complete dissolution is nearly impossible outside of a laboratory, meaning a significant amount of plastic polymers from water-soluble polymers will inevitably enter the environment [36].

1.3. Textiles

It is a fact that textiles are one of the primary sources of microplastics. Approximately 34.8 % of microplastics released into the environment globally come from these woven fabrics or textiles [37]. A notable application of plastic is in the form of fibres which are utilized to produce our clothing as well as textiles that improve the aesthetics and practicality of our living spaces. In the year 2016, approximately 65 million tonnes of plastic were manufactured specifically for textile fibres [38]. The tiny plastic particles that shed from the fabric are known as 'microfibers,' which are essentially small yarns or fractions of yarn [38]. According to a research study, 35 % of primary microplastics present in the oceans worldwide are a result of the washing of synthetic textiles [37]. During washing, microfibers shed and mix readily with water, eventually ending up in sewage treatment plants. When we wash clothes made of synthetic fabrics, plastic threads shed from them end up in our washing machine and eventually in water bodies such as rivers, canals, and oceans. Even after water treatment, the amount of microfibers released is considered negligible.

Despite the preference for cotton, statistics show that about 50 % of cloth production is made from plastic, and washing such clothes releases about 700,000 microfibers per wash [39,40]. By 2050, the clothing industry alone will contribute 2.2 million tons of microplastics to the ocean [41]. These microfibers absorb harmful chemicals like Polychlorinated Biphenyls and Persistent Organic Pollutants as well as fabric additives like plasticizers, temperature-sensitizing chemicals, and antibacterial agents. Aquatic animals can ingest the microfibers and chemicals from textiles that dissolve in water, causing decreased blood flow, oxygen levels, growth, and reproductive capacity. Since humans are omnivores and consume seafood, these issues affect us as well [42,43]. Recently in 2022, it is found that knitted fabrics release a considerably higher amount of microplastics compared to woven fabrics when subjected to identical washing conditions [44].

1.4. Single-use plastic

Plastic products can be recycled and used to create the same or different items after being used and stored. The term "single-use" only applies when the plastic cannot be reused as a raw material. Typically, these single-use plastics are discarded on land and in bodies of water, where around 75 % of them end up as marine debris, classified as micro, meso, or macro debris [45,46]. Approximately 54.5 % of the microplastics that are present in the ocean consist of polyethylene, while polypropylene accounts for 16.5 %. The remaining percentage is made up of various materials such as polyvinyl chloride, polystyrene, polyester, and polyamides [47]. According to experts, approximately 8.3 billion tons of new plastic have been produced, and out of this, 6.3 billion tons of plastic waste has been generated. Shockingly, only 9 % of this waste has been recycled, 12 % has been burnt through incineration, and the remaining 79 % is still present in landfills and the natural environment. Assuming that current patterns persist, the quantity of plastic waste in landfills is projected to reach 12 billion metric tons by 2050. This figure is equivalent to the weight of the Empire State Building multiplied by 35, 000 [48,49]. Starting in 2021, the European Union announced the prohibition of certain single-use items, along with a requirement to decrease the usage of other plastic items by at least 25 % in each member state by 2025. Moreover, the United Kingdom envisages the imposition of a levy on the production and importation of plastic packaging characterized by a recycled plastic content of less than 30 % [45].

1.5. Tires

In 1909, the Bayer Company's scientist Fritz Holfmann created the first synthetic rubber. Currently, tires are composed of approximately 19 % natural rubber and 24 % synthetic rubber, with the remaining portion being comprised of plastic polymer, metal, filler, and additives. Based on research conducted in 2017, the worldwide production of tyre dust amounted to 3.4 million tonnes in 2013 [50]. The annual production of new tires exceeds 1.6 billion, while approximately 1 billion discarded tires are generated yearly [51]. Microplastics are primarily generated in three ways during tire movement on the road surface, including tire wear particles, brake wear particles, and road wear particles [52]. When car tires move, the resulting microplastics can become airborne and remain in the air for extended periods, depending on wind speed and carrying capacity. These airborne microplastics can be inhaled into the human body and settle on the surface of wetlands, soil, and plants.

Fig. 2 presents the percentage of different primary sources of microplastics. It is seen that synthetic textiles constitute the largest

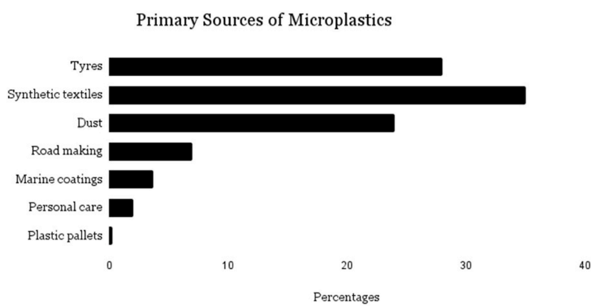

Fig. 2. Percentage of primary sources of microplastics [53].

share at 35 %, followed by tires at 28 %. Dust is another significant contributor, making up 24 % of the microplastic sources while road-making accounts for 7 %. Smaller but notable contributions come from marine coatings (3.7 %) and personal care products (2 %), with plastic pallets being responsible for a relatively minor fraction at just 0.3 %. This data underscores the diverse origins of microplastic sources, highlighting the need for comprehensive strategies to address this environmental concern.

1.6. Microplastics' effect on lung airways

The degree of human exposure to microparticles suspended in the atmosphere is generally dependent on their size [54]. Microparticles are usually divided into four categories: those larger than 10 μm, those smaller than 10 μm, those smaller than 2.5 μm, and ultrafine particles smaller than 0.1 μm. Upon inhalation, particles larger than 10 μm typically collide with the upper airways, whereas particles smaller than 10 μm can enter the bronchioles, and particles smaller than 2.5 μm and ultrafine particles can even penetrate the alveoli [55]. According to a study using human biomonitoring, there was proof of plastic in the lung tissue, indicating that microplastics from the air can deposit and build up in the lungs [56]. Moreover, extended exposure to microplastics can result in respiratory illnesses such as asthma and pneumoconiosis [57,58]. Moreover, fibrous particles that come from synthetic clothing are present everywhere and it's possible to inhale some of them. After entering the respiratory system, the majority of these particles are likely to be caught by the fluid lining the lungs. Nevertheless, certain particles may manage to bypass the lung's natural clearance mechanisms [59]. According to Zhang et al. [60], it is widely accepted that inhalation is the primary route for the uptake of microparticles, as compared to other methods of exposure. It is suggested that as a result of microplastic's diminutive dimensions, humans have the potential to inhale airborne microplastics directly (See Fig. 3) [61,62].

1.7. Microplastic deposition in lung airways

Islam et al. [63] demonstrated microplastic deposition in lung airways. Notably, cylindrical microplastics with diameters of 2.56 and 5.56 μm exhibit higher deposition, while 1.6 μm cylindrical particles show lower rates at a flow rate of 7.5 l/min. Spherical and tetrahedral microplastics display identical deposition rates at this flow rate. Despite this, the overall deposition efficiency at 7.5 l/min exceeds that of 30 l/min for all microplastic sizes. This discrepancy is attributed to the extended residence time at lower flow rates, influencing the passage of microplastics through the upper airway region. Factors like gravitational sedimentation and Brownian diffusion play vital roles, with Brownian diffusion being more pronounced at lower flow rates but diminishing as flow rates increase.

1.8. Experimental approaches for lung airways

In 2018, Prata [64] conducted a study examining how microplastics that humans breathe in affect their respiratory system. The research found that individuals who were exposed to microplastics experienced airway inflammation, which resulted in difficulty breathing or shortness of breath. Amato-Lourenço et al. [65] utilized Raman spectroscopy to explore the existence of microparticles, including polymeric particles and fibers, within human lung tissues. Recently, in a clinical study, it is discovered that airborne microplastics were present in all regions of the human lung airways tissues [66]. The investigation revealed that 23 % of the

Fig. 3. Deposition of microparticles in lungs.

microplastics identified were polypropylene, 18 % were polyethylene terephthalate, and 15 % were resin. Lu et al. [67] provided a short overview of how the presence of microplastics in the air can affect individuals with lung conditions. They recommend that more emphasis should be placed on comprehending its effect on the respiratory health system. Shi et al. [68] carried out an experimental study to examine how microparticles impact human lung surfactants and discovered that being exposed to microparticles could have detrimental effects on respiratory health. Baeza-Martínez et al. [69] detected the presence of microplastics in the lower airway of European citizens. They found the existence of microparticles in the lower respiratory system, particularly in individuals who smoke.

Airborne minuscule plastic particles can effortlessly infiltrate our body via the respiratory pathways when we inhale. Consequently, these plastic particles may exert various influences on our cells, tissues, and other bodily organs. A recent investigation conducted by Khan and Jia [70] observed that microplastics and their toxic substances can be readily assimilated by the delicate alveolar epithelium, leading to localized inflammation. Subsequently, they are transported throughout the entire circulatory system, giving rise to systemic predicaments or provoking the generation of pro-inflammatory factors, thereby causing inflamed conditions. It can have multiple effects on our body and lead to conditions such as asthma, pneumonia, allergic reactions, and deformations in the bronchial tissue, among others. Islam et al. [63] conducted an investigation on the intricate dynamics of microplastics' transportation and deposition within the upper respiratory system. The study regarded microplastics as conventional airborne particles that eventually settle within the airways. In order to use a CFD approach, the researchers incorporated the specific shapes and sizes of the microplastics, employing a similar methodology used for handling other particle types which can be considered a major limitation of the study. While previous studies have not focused on the deposition of such plastics within the airways, studying the transportation and deposition of microplastics alone does not fully capture the real-life implications for the human respiratory system. Instead, a more significant discovery can be achieved by analyzing the interactions between microplastics and mucus as well as the epithelial tissues. Such an investigation may provide a deeper understanding of the impact of microplastics in the human airways, which cannot be effectively achieved using CFD alone.

1.9. CFD approaches to model lung airways

CFD has been extensively used to study particle deposition in lung airways [71,72]. These studies aim to understand the mechanisms and factors influencing the settling of particles inhaled into the respiratory tract. Here is a summary of some of the key findings from CFD studies on particle deposition in lung airways.

- *Particle size:* The settling of particles inhaled into the respiratory tract is highly dependent on their size. Smaller particles ($PM_{2.5}$ and less size) have a higher likelihood of reaching deeper regions within the lungs, while larger particles (PM_{10} or higher size) have an increased probability of being accumulated in the upper respiratory passages.
- *Flow rate and breathing pattern:* The flow rate and breathing pattern can significantly affect particle deposition [73]. Inhalation at a slower flow rate and a deeper breath can increase deposition in the lower airways.
- *Airway geometry:* The geometry of the airways, including the diameter and branching angles, can affect particle deposition. Narrower and more tortuous airways are more likely to deposit particles compared to wider and straighter airways.
- *Gravity:* Gravity can also play a role in particle deposition, particularly in the larger airways. Deposition is more likely to occur in the lower regions of the lung due to gravitational settling.
- *Particle shape:* The shape of the particles can also affect deposition. Irregularly shaped particles are more likely to deposit in the airways compared to spherical particles of the same size.
- *Morphology of the lung:* Lung surfactant and mucus movement also play important roles in airflow movement, particle residence, and proper compliance and recoil of lung alveolar [74].
- *Boundary conditions:* Most of the CFD studies, including the recent work [63], used the inlet as a boundary condition of the mouth or nose or trachea from where particles and air enter the lung airways. The outlet is specified at the end of the bronchioles. The wall boundary condition they used is the "Trap" condition, which means if any particles touch the wall, they should be deposited, which is true as the airways wall is covered with very sticky mucus layer.

Chemical properties of the particle can also influence particle deposition in the lung. The chemical composition of particles can affect their interaction with the lung tissue and respiratory fluids, which in turn can influence their deposition behavior and these factors should be considered when assessing the health effects of inhaled particles. It is noted that once the particles are deposited in the lung, CFD cannot analyze how they interact with the mucus and epithelial tissues. If we consider the mucus movement and deposited particle interaction, it may show that particles will move with mucus and be cleared from the lung. However, modelling mucus flow and the particle airflow in the whole lung is extremely complex. Also, toxicity, solubility, surface chemistry, and volatility of the particles may not be possible to model using CFD. Some software, like COMSOL Multiphysics, has a Chemical Reaction Module which can be used to try. To the authors' knowledge, there is no study available on such problems.

1.10. Some of the advantages of CFD for lung applications are

- CFD can provide detailed and local information on the flow dynamics and aerosol deposition in the human airways, which can help to understand the mechanisms and factors that affect lung function and disease.

- It can enable parametric studies and sensitivity analysis to investigate the effects of different variables and scenarios on the airflow and aerosol motion in the lung, such as breathing patterns, inhalation statuses, environmental conditions, aerosol properties, and lung geometry.
- It can facilitate the design and optimization of medical devices and treatments for lung diseases, such as inhalers, nebulizers, ventilators, bronchodilators, and anti-inflammatory drugs.
- This modelling can help to reduce the need for animal testing and human trials by providing reliable and realistic simulations of lung airflow and aerosol deposition, which can save time, money, and ethical issues.
- CFD can offer a flexible and versatile tool to model different aspects and scales of the lung airflow and aerosol motion, such as laminar or turbulent flow, single-phase or multiphase flow, steady-state or transient flow, and idealised or realistic geometry.
- This numerical model can complement and enhance the in vivo and in vitro measurements of lung airflow and aerosol deposition by providing additional information that is difficult or impossible to obtain experimentally, such as local pressure, velocity, shear stress, and deposition efficiency.
- Computational modelling techniques can support the personalized medicine approach for lung diseases by providing patient-specific simulations of lung airflow and aerosol deposition based on individual lung geometry, boundary conditions, and flow parameters.
- CFD can contribute to public health awareness and prevention of lung diseases by providing simulations of bioaerosol motion and transmission in human airways, such as COVID-19.
- It can foster multidisciplinary collaboration among engineers, physicists, biologists, clinicians, and epidemiologists to address the complex and multifaceted problems related to lung function and disease. It can stimulate scientific discovery and innovation in the field of lung research by providing new insights and hypotheses on airflow and aerosol motion in the human airways.

1.11. Some of the challenges or limitations of CFD for lung applications are

- The size and complexity of the complete, multiscale geometry of the bronchopulmonary tree, make it difficult to model the entire lung with high resolution and accuracy.
- The uncertainty and variability of the lung geometry, boundary conditions, and flow parameters, depend on factors such as age, gender, health status, breathing pattern, and posture.
- The computational cost and time required to perform CFD simulations for lung airflow, especially for transient and multiphase problems.
- The validation and verification of CFD results require experimental data or clinical measurements that are often scarce or unavailable.
- The difficulty of capturing the transient and nonlinear behavior of the airflow and aerosol motion in the human airways, especially under different breathing patterns, inhalation statuses, and environmental conditions.
- The lack of reliable and consistent data on the anatomical features and morphometry of healthy and diseased lungs, which vary greatly among individuals and populations.
- The influence of distinctive characteristics and pivotal advancements in numerical techniques, such as turbulence models, mesh generation, boundary conditions, and solver algorithms, on the accuracy and robustness of CFD simulations.
- The need for multidisciplinary collaboration among engineers, physicists, biologists, clinicians, and epidemiologists to address the complex and multifaceted problems related to lung function and disease.
- In this study, we reviewed microplastic deposition in human lungs and how computational study can help us understand the problem and its limitations. Computational fluid dynamics can predict the local particle deposition, which gives us an idea about the deposition hotspot and indicates some consequences. However, it cannot predict what happens after the particle is deposited. To understand this, one needs to study molecular dynamics simulations, which are absent in the literature.

2. Conclusion

Research on the long-term effects of microplastic deposition in the human lung is still limited, and more studies are needed to draw definitive conclusions. Microplastics are minuscule plastic fragments with dimensions smaller than 5 mm. They can be disseminated into the ecosystem through diverse outlets, including the disintegration of larger plastic artifacts, microbeads found in personal care commodities, and the shedding of fibers from synthetic apparel. Inhalation is one potential route of exposure, where microplastics can be deposited in the respiratory system, including the lungs. Studies suggest that microplastics can enter the respiratory system and deposit in the lungs due to their small size. Unlike larger particles, which are often trapped in the upper respiratory tract or expelled through coughing or sneezing, microplastics may have limited clearance mechanisms, making them more likely to accumulate in the lungs. Microplastic particles in the lungs may trigger an inflammatory response. Studies conducted on animals have demonstrated that the existence of microplastics may precipitate inflammation in pulmonary tissue. Inflammation is the body's natural defence mechanism against foreign substances, and chronic inflammation may have adverse health effects over time. Although the long-term consequences of microplastic deposition in the human lung are not yet fully understood, several potential health implications have been suggested. The inhalation of microplastics may conduce to respiratory manifestations, encompassing coughing, wheezing, and dyspnea. Furthermore, the accrual of microplastics within the pulmonary milieu has the potential to exacerbate pre-existing respiratory afflictions, such as asthma or COPD. Microplastics can potentially migrate from the lungs to other organs and tissues, although the extent and implications of this translocation are still being studied. There is concern that microplastics may enter the bloodstream and reach distant organs, potentially leading to systemic health effects. Microplastics can adsorb and accumulate various chemical pollutants from the environment, including persistent organic pollutants (POPs) and heavy metals. If microplastics release these adsorbed chemicals in the lung tissue, it could lead to additional toxicological effects. Despite the growing concern over microplastic pollution, more research is needed to understand the precise mechanisms of microplastic deposition, their distribution in lung tissue, and the long-term health consequences. Subsequent investigations should prioritize the exploration of the potential cytotoxicity inherent in microplastics, and the associated risks they may pose to human health. It is a very hot topic for researchers at this moment. That's why the field of microplastic research is rapidly evolving, and new findings are emerging.

Data availability statement

All data is available in the manuscript.

Ethics Declarations Review and/or approval by an ethics

Committee was not needed for this study because this research did not involve any human or animal participation.

CRediT authorship contribution statement

Suvash C. Saha: Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Goutam Saha:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

References

[1] R.C. Thompson, Y. Olsen, R.P. Mitchell, A. Davis, S.J. Rowland, Anthony W.G. John, D. McGonigle, A.E. Russell, Lost at sea: where is all the plastic? Science (American Association for the Advancement of Science) 304 (5672) (2004) 838, https://doi.org/10.1126/science.1094559, 838.
[2] J. Gasperi, S.L. Wright, R. Dris, F. Collard, C. Mandin, M. Guerrouache, V. Langlois, F.J. Kelly, B. Tassin, Microplastics in air: are we breathing it in? Curr. Opin. Environ. Sci. & Health 1 (2018) 1–5, https://doi.org/10.1016/j.coesh.2017.10.002.
[3] J.P.G.L. Frias, R. Nash, Microplastics: finding a consensus on the definition, Mar. Pollut. Bull. 138 (2019) 145–147, https://doi.org/10.1016/j.marpolbul.2018.11.022.
[4] J.S. Weis, Aquatic microplastic research-A critique and suggestions for the future, Water (Basel) 12 (5) (2020) 1475, https://doi.org/10.3390/w12051475.
[5] J. Lee, J.S. Lee, Y.C. Jang, S.Y. Hong, W.J. Shim, Y.K. Song, S.H. Hong, M. Jang, G.M. Han, D. Kang, S. Hong, Distribution and size relationships of plastic marine debris on beaches in South Korea, Arch. Environ. Contam. Toxicol. 69 (3) (2015) 288–298, https://doi.org/10.1007/s00244-015-0208-x.
[6] J. Gigault, A. ter Halle, M. Baudrimont, P.-Y. Pascal, F. Gauffre, T.-L. Phi, H. El Hadri, B. Grassl, S. Reynaud, Current opinion: what is a nanoplastic? Environ. Pollut. 235 (2018) 1030–1034, https://doi.org/10.1016/j.envpol.2018.01.024, 1987.
[7] S.M. Bashir, S. Kimiko, C.-W. Mak, J.K.-H. Fang, D. Gonçalves, Personal care and cosmetic products as a potential source of environmental contamination by microplastics in a densely populated asian city, Front. Mar. Sci. 8 (2021), https://doi.org/10.3389/fmars.2021.683482.
[8] F. Haque, C. Fan, Fate of microplastics under the influence of climate change, iScience 26 (9) (2023), https://doi.org/10.1016/j.isci.2023.107649, 107649–107649.
[9] S.-J. Royer, S. Ferrón, S.T. Wilson, D.M. Karl, Production of methane and ethylene from plastic in the environment, PLoS One 13 (8) (2018) e0200574–e0200574, https://doi.org/10.1371/journal.pone.0200574.
[10] Y.S. Jung, V. Sampath, M. Prunicki, J. Aguilera, H. Allen, D. LaBeaud, E. Veidis, M. Barry, B. Erny, L. Patel, C. Akdis, M. Akdis, K. Nadeau, Characterization and regulation of microplastic pollution for protecting planetary and human health, Environmental Pollution (1987) 315 (2022) 120442, https://doi.org/10.1016/j.envpol.2022.120442, 120442.
[11] OECD, Plastic Leakage and Greenhouse Gas Emissions Are Increasing, 2022. Link: https://www.oecd.org/environment/plastics/increased-plastic-leakage-and-greenhouse-gas-emissions.htm.
[12] WWF, Simple Changes to Reduce Your Plastic Footprint, 2021. Link, https://wwf.org.au/blogs/simple-changes-to-reduce-your-plastic-footprint/?rd=1#gs.wj1dn2.
[13] C. Campanale, C. Massarelli, I. Savino, V. Locaputo, V.F. Uricchio, A detailed review study on potential effects of microplastics and additives of concern on human health, Int. J. Environ. Res. Publ. Health 17 (4) (2020) 1212, https://doi.org/10.3390/ijerph17041212.
[14] Z. Lett, A. Hall, S. Skidmore, N.J. Alves, Environmental microplastic and nanoplastic: exposure routes and effects on coagulation and the cardiovascular system, Environ. Pollut. (2021), https://doi.org/10.1016/j.envpol.2021.118190, 1987), 291, 118190–118190.
[15] G.M. Zarus, C. Muianga, C.M. Hunter, R.S. Pappas, A review of data for quantifying human exposures to micro and nanoplastics and potential health risks, Sci. Total Environ. 756 (2021) 144010, https://doi.org/10.1016/j.scitotenv.2020.144010, 144010.
[16] S. Wieland, A. Balmes, J. Bender, J. Kitzinger, F. Meyer, A.F. Ramsperger, F. Roeder, C. Tengelmann, B.H. Wimmer, C. Laforsch, H. Kress, From properties to toxicity: comparing microplastics to other airborne microparticles, J. Hazard Mater. 428 (2022), https://doi.org/10.1016/j.jhazmat.2021.128151, 128151–128151.
[17] W. Li, H.-S. Lo, H.-M. Wong, M. Zhou, C.-Y. Wong, N.F.-Y. Tam, S.-G. Cheung, Heavy metals contamination of sedimentary microplastics in Hong Kong, Mar. Pollut. Bull. 153 (2020) 110977, https://doi.org/10.1016/j.marpolbul.2020.110977, 110977.
[18] M. Tarasco, P.J. Gavaia, A. Bensimon-Brito, F.P. Cordelières, T. Santos, G. Martins, D.T. de Castro, N. Silva, E. Cabrita, M.J. Bebianno, D.Y.R. Stainier, M. L. Cancela, V. Laizé, Effects of pristine or contaminated polyethylene microplastics on zebrafish development, Chemosphere 303 (Pt 3) (2022) 135198, https://doi.org/10.1016/j.chemosphere.2022.135198, 135198.
[19] K. James, K. Vasant, S. Padua, V. Gopinath, S. K, A.R. J, A. Babu, S. John, An assessment of microplastics in the ecosystem and selected commercially important fishes off Kochi, southeastern Arabian Sea, India, Mar. Pollut. Bull. 154 (2020) 111027, https://doi.org/10.1016/j.marpolbul.2020.111027, 111027.
[20] D.B. Daniel, P.M. Ashraf, S.N. Thomas, K.T. Thomson, Microplastics in the edible tissues of shellfishes sold for human consumption, Chemosphere 264 (Pt 2) (2021) 128554, https://doi.org/10.1016/j.chemosphere.2020.128554.

[21] C.J. Thiele, L.J. Grange, E. Haggett, M.D. Hudson, P. Hudson, A.E. Russell, L.M. Zapata-Restrepo, Microplastics in European sea salts – an example of exposure through consumer choice and of interstudy methodological discrepancies, Ecotoxicol. Environ. Saf. 255 (2023) 114782, https://doi.org/10.1016/j.ecoenv.2023.114782, 114782.

[22] C. Di Fiore, M.P. Sammartino, C. Giannattasio, P. Avino, G. Visco, Microplastic contamination in commercial salt: an issue for their sampling and quantification, Food Chem. 404 (2023) 134682, https://doi.org/10.1016/j.foodchem.2022.134682, 134682.

[23] L. Montano, E. Giorgini, V. Notarstefano, T. Notari, M. Ricciardi, M. Piscopo, O. Motta, Raman Microspectroscopy Evidence of Microplastics in Human Semen, vol. 901, The Science of the Total Environment, 2023, p. 165922, https://doi.org/10.1016/j.scitotenv.2023.165922, 165922.

[24] A. Ragusa, A. Svelato, C. Santacroce, P. Catalano, V. Notarstefano, O. Carnevali, F. Papa, M.C.A. Rongioletti, F. Baiocco, S. Draghi, E. D'Amore, D. Rinaldo, M. Matta, E. Giorgini, Plasticenta: first evidence of microplastics in human placenta, Environ. Int. 146 (2021) 106274, https://doi.org/10.1016/j.envint.2020.106274.

[25] H.A. Leslie, M.J.M. van Velzen, S.H. Brandsma, A.D. Vethaak, J.J. Garcia-Vallejo, M.H. Lamoree, Discovery and quantification of plastic particle pollution in human blood, Environ. Int. 163 (2022) 107199, https://doi.org/10.1016/j.envint.2022.107199, 107199.

[26] T. Ali, A. Habib, F. Muskan, S. Mumtaz, R. Shams, Health risks posed by microplastics in tea bags: microplastic pollution - a truly global problem, Int. J. Surg. 109 (3) (2023) 515–516, https://doi.org/10.1097/JS9.0000000000000055.

[27] P. Makhdoumi, M. Pirsaheb, A.A. Amin, S. Kianpour, H. Hossini, Microplastic pollution in table salt and sugar: occurrence, qualification and quantification and risk assessment, J. Food Compos. Anal. 119 (2023) 105261, https://doi.org/10.1016/j.jfca.2023.105261.

[28] M.D. Caba-Flores, C. Martínez-Valenzuela, M. Cárdenas-Tueme, A. Camacho-Morales, Micro problems with macro consequences: accumulation of persistent organic pollutants and microplastics in human breast milk and in human milk substitutes, Environ. Sci. Pollut. Res. Int. 30 (42) (2023) 95139–95154, https://doi.org/10.1007/s11356-023-29182-5.

[29] S. D'Angelo, R. Meccariello, Microplastics: a threat for male fertility, Int. J. Environ. Res. Publ. Health 18 (5) (2021) 1–11, https://doi.org/10.3390/ijerph18052392.

[30] E. Persiani, A. Cecchettini, E. Ceccherini, I. Gisone, M.A. Morales, F. Vozzi, Microplastics: a matter of the heart (and vascular system), Biomedicines 11 (2) (2023) 264, https://doi.org/10.3390/biomedicines11020264.

[31] Krystal Vasquez, Researchers find microplastics in clouds, C & EN Global Enterprise 101 (33) (2023) 17, https://doi.org/10.1021/cen-10133-polcon3, 17.

[32] PSF (Plastic Soup Foundation), EU ban on microplastics in cosmetics: too slow and too limited, Link, https://www.plasticsoupfoundation.org/en/2023/03/eu-ban-on-microplastics-in-cosmetics-too-slow-and-too-limited/, 2023.

[33] H.A. Leslie, Review of Microplastics in Cosmetics: Scientific Background on a Potential Source of Plastic Particulate Marine Litter to Support Decision-Making, 2014.

[34] E. Chiellini, A. Corti, R. Solaro, Biodegradation of poly(vinyl alcohol) based blown films under different environmental conditions, Polym. Degrad. Stabil. 64 (2) (1999) 305–312, https://doi.org/10.1016/S0141-3910(98)00206-7.

[35] S. Xu, M.A. Malik, Z. Qi, B. Huang, Q. Li, M. Sarkar, Influence of the PVA fibers and SiO2 NPs on the structural properties of fly ash based sustainable geopolymer, Construct. Build. Mater. 164 (2018) 238–245, https://doi.org/10.1016/j.conbuildmat.2017.12.227.

[36] H.P.H. Arp, H. Knutsen, Could we spare a moment of the spotlight for persistent, water-soluble polymers? Environ. Sci. Technol. 54 (1) (2020) 3–5, https://doi.org/10.1021/acs.est.9b07089.

[37] J. Boucher, D. Friot, Primary Microplastics in the Oceans: a Global Evaluation of Sources, IUCN, en, 2017, https://doi.org/10.2305/IUCN.CH.2017.01.

[38] B. Henry, K. Laitala, I.G. Klepp, Microfibres from apparel and home textiles: prospects for including microplastics in environmental sustainability assessment, Sci. Total Environ. 652 (2019) 483–494, https://doi.org/10.1016/j.scitotenv.2018.10.166.

[39] S. Opperskalski, S. Siew, E. Tan, L. Truscott, Preferred Fiber & Materials Market Report, 2020.

[40] I.E. Napper, R.C. Thompson, Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions, Mar. Pollut. Bull. 112 (1–2) (2016) 39–45, https://doi.org/10.1016/j.marpolbul.2016.09.025.

[41] Ellen MacArthur Foundation, A new textiles economy: redesigning fashion's future, Link: https://ellenmacarthurfoundation.org/a-new-textiles-economy, 2017.

[42] A.A. Koelmans, A. Bakir, G.A. Burton, C.R. Janssen, Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies, Environ. Sci. Technol. 50 (7) (2016) 3315–3326, https://doi.org/10.1021/acs.est.5b06069.

[43] B. Henry, K. Laitala, I.G. Klepp, Microplastic Pollution from Textiles: A Literature Review, Consumption Research Norway, Oslo, 2018.

[44] H. Cui, C. Xu, Study on the relationship between textile microplastics shedding and fabric structure, Polymers 14 (23) (2022) 5309, https://doi.org/10.3390/polym14235309.

[45] I.E. Napper, R.C. Thompson, Plastic debris in the marine environment: history and future challenges, Glob. Chall. 4 (6) (2020) 1900081, https://doi.org/10.1002/gch2.201900081 n/a.

[46] G.G.N. Thushari, J.D.M. Senevirathna, Plastic pollution in the marine environment, Heliyon 6 (8) (2020) e04709–e04709, https://doi.org/10.1016/j.heliyon.2020.e04709.

[47] M.N. Issac, B. Kandasubramanian, Effect of microplastics in water and aquatic systems, Environ. Sci. Pollut. Res. Int. 28 (16) (2021) 19544–19562, https://doi.org/10.1007/s11356-021-13184-2.

[48] R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made, Sci. Adv. 3 (7) (2017) e1700782–e1700782, https://doi.org/10.1126/sciadv.1700782.

[49] C.J. Rhodes, Plastic pollution and potential solutions, Sci. Prog. 101 (3) (2018) 207–260, https://doi.org/10.3184/003685018X15294876706211, 1916.

[50] P. Jan Kole, A.J. Löhr, F.G.A.J. Van Belleghem, A.M.J. Ragas, Wear and tear of tyres: a stealthy source of microplastics in the environment, Int. J. Environ. Res. Publ. Health 14 (10) (2017) 1265, https://doi.org/10.3390/ijerph14101265.

[51] R. Saputra, R. Walvekar, M. Khalid, N.M. Mubarak, M. Sillanpää, Current progress in waste tire rubber devulcanization, Chemosphere 265 (2021) 129033, https://doi.org/10.1016/j.chemosphere.2020.129033.

[52] F. Sommer, V. Dietze, A. Baum, J. Sauer, S. Gilge, C. Maschowski, R. Gieré, Tire abrasion as a major source of microplastics in the environment, Aerosol Air Qual. Res. 18 (8) (2018) 2014–2028, https://doi.org/10.4209/aaqr.2018.03.0099.

[53] M. Fiore, S. Fraterrigo Garofalo, A. Migliavacca, A. Mansutti, D. Fino, T. Tommasi, Tackling marine microplastics pollution: an overview of existing solutions, Water Air Soil Pollut. 233 (7) (2022), https://doi.org/10.1007/s11270-022-05715-5.

[54] W. Chen, D.W. Fryrear, Aerodynamic and geometric diameters of airborne particles, J. Sediment. Res. 71 (3) (2001) 365–371, https://doi.org/10.1306/2DC4094A-0E47-11D7-8643000102C1865D.

[55] F.J. Kelly, J.C. Fussell, Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter, Atmos. Environ. 60 (2012) 504–526, https://doi.org/10.1016/j.atmosenv.2012.06.039, 1994.

[56] J.L. Pauly, S.J. Stegmeier, H.A. Allaart, R.T. Cheney, P.J. Zhang, A.G. Mayer, R.J. Streck, Inhaled cellulosic and plastic fibers found in human lung tissue, Cancer Epidemiol. Biomarkers Prev. 7 (5) (1998) 419–428.

[57] S. Atis, B. Tutluoglu, E. Levent, C. Ozturk, A. Tunaci, K. Sahin, A. Saral, I. Oktay, A. Kanik, B. Nemery, The respiratory effects of occupational polypropylene flock exposure, Eur. Respir. J. 25 (1) (2005) 110–117, https://doi.org/10.1183/09031936.04.00138403.

[58] S.E. Turcotte, A. Chee, R. Walsh, F.C. Grant, G.M. Liss, A. Boag, L. Forkert, P.W. Munt, M.D. Lougheed, Flock worker's lung disease: natural history of cases and exposed workers in Kingston, Ontario, Chest 143 (6) (2013) 1642–1648, https://doi.org/10.1378/chest.12-0920.

[59] S.L. Wright, F.J. Kelly, Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (12) (2017) 6634–6647, https://doi.org/10.1021/acs.est.7b00423.

[60] Q. Zhang, E.G. Xu, J. Li, Q. Chen, L. Ma, E.Y. Zeng, H. Shi, A review of microplastics in table salt, drinking water, and air: direct human exposure, Environ. Sci. Technol. 54 (7) (2020) 3740–3751, https://doi.org/10.1021/acs.est.9b04535.

[61] A. Tunahan Kaya, M. Yurtsever, S. Çiftçi Bayraktar, Ubiquitous exposure to microfiber pollution in the air, Eur. Phys. J. Plus 133 (11) (2018) 1–9, https://doi.org/10.1140/epjp/i2018-12372-7.

[62] G. Chen, Q. Feng, J. Wang, Mini-review of microplastics in the atmosphere and their risks to humans, Sci. Total Environ. 703 (2020) 135504, https://doi.org/10.1016/j.scitotenv.2019.135504, 135504.
[63] M.S. Islam, M.M. Rahman, P. Larpruenrudee, A. Arsalanloo, H.M. Beni, M.A. Islam, Y. Gu, E. Sauret, How microplastics are transported and deposited in realistic upper airways? Phys. Fluids (6) (2023) 35, https://doi.org/10.1063/5.0150703, 1994.
[64] J.C. Prata, Airborne microplastics: consequences to human health? Environ. Pollut. 234 (2018) 115–126, https://doi.org/10.1016/j.envpol.2017.11.043, 1987.
[65] L.F. Amato-Lourenço, R. Carvalho-Oliveira, G.R. Júnior, L. dos Santos Galvão, R.A. Ando, T. Mauad, Presence of airborne microplastics in human lung tissue, J. Hazard Mater. 416 (2021) 126124, https://doi.org/10.1016/j.jhazmat.2021.126124, 126124.
[66] L.C. Jenner, J.M. Rotchell, R.T. Bennett, M. Cowen, V. Tentzeris, L.R. Sadofsky, Detection of microplastics in human lung tissue using μFTIR spectroscopy, Sci. Total Environ. 831 (2022) 154907, https://doi.org/10.1016/j.scitotenv.2022.154907, 154907.
[67] K. Lu, D. Zhan, Y. Fang, L. Li, G. Chen, S. Chen, L. Wang, Microplastics, potential threat to patients with lung diseases, Front. Toxicol. 4 (2022) 958414, https://doi.org/10.3389/ftox.2022.958414.
[68] W. Shi, Y. Cao, X. Chai, Q. Zhao, Y. Geng, D. Liu, S. Tian, Potential health risks of the interaction of microplastics and lung surfactant, J. Hazard Mater. 429 (2022) 128109, https://doi.org/10.1016/j.jhazmat.2021.128109, 128109.
[69] C. Baeza-Martínez, S. Olmos, M. González-Pleiter, J. López-Castellanos, E. García-Pachón, M. Masiá-Canuto, L. Hernández-Blasco, J. Bayo, First evidence of microplastics isolated in European citizens' lower airway, J. Hazard Mater. 438 (2022) 129439, https://doi.org/10.1016/j.jhazmat.2022.129439, 129439.
[70] A. Khan, Z. Jia, Recent insights into uptake, toxicity, and molecular targets of microplastics and nanoplastics relevant to human health impacts, iScience 26 (2) (2023) 106061, https://doi.org/10.1016/j.isci.2023.106061, 106061.
[71] M.S. Islam, S.C. Saha, T. Gemci, I.A. Yang, E. Sauret, Z. Ristovski, Y.T. Gu, Euler-Lagrange prediction of diesel-exhaust polydisperse particle transport and deposition in lung: anatomy and turbulence effects, Sci. Rep. 9 (1) (2019) 12423, https://doi.org/10.1038/s41598-019-48753-6, 16.
[72] M.S. Islam, G. Paul, H.X. Ong, P.M. Young, Y.T. Gu, S.C. Saha, A review of respiratory anatomical development, air flow characterization and particle deposition, Int. J. Environ. Res. Publ. Health 17 (2) (2020) 380, https://doi.org/10.3390/ijerph17020380.
[73] I. Francis, S.C. Saha, Computational fluid dynamics and machine learning algorithms analysis of striking particle velocity magnitude, particle diameter, and impact time inside an acinar region of the human lung, Phys. Fluids (10) (2022) 34, https://doi.org/10.1063/5.0106594, 1994.
[74] I. Francis, S.C. Saha, Surface tension effects on flow dynamics and alveolar mechanics in the acinar region of human lung, Heliyon 8 (10) (2022) e11026–e11026, 10.1016/j.heliyon.2022.e11026.