(Review Article)

The Impact of PM 2.5 on Pulmonary Immunophysiology and The Lung Microbiome

Raynhuga Nabunyareuk[1], Pavarisa Thepsena[2], Panissara Ingkapak[2], Punnisa Phongthanapanich[3], Pincha Tantisak[4], Pannapat Srikullayanunt[5], Anshisa Phongchaisrikun[6], Sathid Aimjongjun[7]*

[1]KPIS International School, 58 Moo 9 Soi Ram Intra 34, Tha Raeng, Bang Khen, Bangkok, Thailand

[2]Samsenwitthayalai School, 132 11 Rama VI Rd, Khet Phaya Thai, Bangkok, Thailand

[3]Patumwan Demonstration School Srinakharinwirot University, 2 Henri Dunant Rd., Pathum Wan, Bangkok, Thailand

[4]Suankularb Wittayalai Thonburi School, Moo 6, 201 Kanchanapisek Road, Tha Kham, Bang Khun Thian, Bangkok, Thailand

[5]Mahidol University International Demonstration School, 7/11 Moo 4, Sanamchai, Muang, Suphanburi, Thailand

[6]Triamudom Suksa School, 227 Phaya Thai Rd. Pathum Wan, Bangkok, Thailand

[7]Department of Fundamental and Medical Sciences, Faculty of Allied Health Sciences, Pathumthani University, 40 Santi Suk, Mu 4 Alley, Ban Klang, Mueang Pathum Thani District, Pathum Thani, Thailand

Correspondence to : sathid.a@ptu.ac.th

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Abstract

Air pollution is a ubiquitous environmental challenge, with fine particulate matter (PM 2.5) being a prominent component, originating from diverse sources including combustion, dust, soil, biological particles, and sea salt aerosols. This review delves into the complex interplay between PM 2.5 and its various sources, summarize main finding and elucidating their multifaceted impact on the pulmonary immune system and lung microbiome. PM 2.5, characterized by distinct compositions and biological constituents, can evoke inflammatory responses, oxidative stress, and immune dysregulation within the respiratory tract, precipitating a range of respiratory ailments. Concurrently, PM 2.5 can exert influences on the lung microbiome, potentially unsettling microbial equilibrium and compromising its protective functions. Dysbiosis induced by PM 2.5 exposure may not only compromise immune defenses but also extend its influence via the gut-lung axis, impacting systemic health. Addressing the pernicious effects of PM 2.5 necessitates a holistic approach, encompassing stringent air quality regulations, emission reductions, cleaner energy promotion, and public awareness. Moreover, further research endeavors are indispensable to unravel the intricate interactions and develop targeted interventions that mitigate PM 2.5-induced perturbations in lung immunophysiology and the microbiome. This comprehensive understanding is pivotal in fostering cleaner air, healthier lungs, and enhanced overall healthiness on a global scale. Additionally, it also helps in development of portable air quality sensors, air quality trends research and conduct comprehensive studies to further elucidate the health effects of different air pollutants, including their long-term impacts on respiratory health.

Keywords : Immunophysiology, Microbiome, PM 2.5, Oxidative stress

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(บทความฟื้นฟูวิชาการ)

ผลกระทบของฝุ่นละอองขนาดเล็ก PM 2.5 ต่อสรีรวิทยาภูมิคุ้มกัน และจุลินทรีย์ไมโครไบโอมในปอด

เรณุกา ณปุณยฤกษ์[1], ปวริศา เทพเสนา[2], ปาณิสรา อิงคภาคย์[2],ปุญณิศา พงศ์ธนาพาณิช[3], ปิญชาน์ ตันติศักดิ์[4], อัญชิสา พงศ์ชัยศรีกุล[5], พรรณพชร ศรีกุลยนันทน์[6], สาธิต เอี่ยมจงจันทร์[7]

[1]โรงเรียนนานาชาติกีรพัฒน์ 58 หมู่ 9 ซอยอยู่เย็น ถนนรามอินทรา 34 แขวงท่าแร้ง เขตบางเขน กทม.

[2]โรงเรียนสามเสนวิทยาลัย 132/11 ถนนพระราม 6 แขวงพญาไท เขตพญาไท กทม.

[3]โรงเรียนสาธิตมหาวิทยาลัยศรีนครินทรวิโรฒ ปทุมวัน 2 ถนนอังรีดูนังต์ แขวงปทุมวัน, เขตปทุมวัน, กทม.

[4]โรงเรียนสวนกุหลาบวิทยาลัย ธนบุรี 201 ถนนกาญจนาภิเษก(เลียบทางด่วนสายบางขุนเทียน-พระประแดง) แขวงท่าข้าม เขตบางขุนเทียน กทม.

[5]โรงเรียนสาธิตนานาชาติ มหาวิทยาลัยมหิดล อาคารมหิดลอดุลยเดช พระศรีนครินทร ชั้น 3 999 ถนนพุทธมณฑลสาย 4 ต.ศาลายา อ.พุทธมณฑล นครปฐม

[6]โรงเรียนเตรียมอุดมศึกษา 227 ถนนพญาไท เขตปทุมวัน กทม.

[7]ภาควิชาวิทยาศาสตร์พื้นฐานและวิทยาศาสตร์การแพทย์ คณะสหเวชศาสตร์ มหาวิทยาลัยปทุมธานี 140 หมู่ 4 ถนนติวานนท์ ต.บ้านกลาง อ.เมืองปทุมธานี จ.ปทุมธานี

บทคัดย่อ

มลพิษทางอากาศเป็นความท้าทายด้านสิ่งแวดล้อมที่สำคัญ โดยมีฝุ่นละอองขนาดเล็ก (PM 2.5) เป็นปัจจัยหลัก ซึ่งมีต้นกำเนิดมาจากแหล่งต่าง ๆ ได้แก่ การเผาไหม้ ฝุ่น ดิน อนุภาคทางชีวภาพ และฝุ่นเกลือทะเล บทความนี้ทำการวิเคราะห์ถึงความสัมพันธ์ระหว่าง PM 2.5 กับแหล่งกำเนิด และได้สรุปถึงผลกระทบต่อระบบสรีรวิทยาภูมิคุ้มกันและจุลินทรีย์ไมโครไบโอมในปอด ฝุ่น PM 2.5 มีองค์ประกอบทางชีวภาพที่แตกต่างกัน ทำให้เกิดปฏิกิริยาการอักเสบ ภาวะเครียดที่เกิดจากออกซิเดชั่น (oxidative stress) และการควบคุมระบบภูมิคุ้มกันที่ผิดปกติภายในระบบทางเดินหายใจ ส่งผลให้เกิดโรคระบบทางเดินหายใจได้หลายประเภท ในขณะเดียวกัน PM 2.5 ก็สามารถมีอิทธิพลต่อไมโครไบโอมในปอด ซึ่งอาจทำให้เกิดความไม่สมดุลของจุลินทรีย์และส่งผลต่อหน้าที่ในการปกป้องร่างกาย ภาวะ dysbiosis ที่เกิดจากการสัมผัส PM 2.5 ไม่เพียงแต่ส่งผลต่อภาวะภูมิคุ้มกันเท่านั้น แต่ยังส่งผลต่อระบบความสัมพันธ์ของลำไส้และปอด (gut-lung axis) ซึ่งมีผลเสียต่อสุขภาพของร่างกาย การจัดการกับผลกระทบที่เป็นอันตรายของ PM 2.5 จำเป็นต้องมีแนวทางแบบองค์รวม ซึ่งครอบคลุมกฎระเบียบด้านคุณภาพอากาศที่เข้มงวด การลดการปล่อยก๊าซเรือนกระจก การส่งเสริมพลังงานที่สะอาด ตลอดจนสร้างความตระหนักรู้ของสาธารณชน นอกจากนี้ควรมีการศึกษาวิจัยเพิ่มเติมเพื่อแก้ปัญหาและพัฒนามาตรการที่ช่วยลดผลเสียที่เกิดจาก PM 2.5 ต่อสรีรวิทยาภูมิคุ้มกันของปอดและไมโครไบโอม ความเข้าใจที่ครอบคลุมนี้จะมีส่วนสำคัญในการส่งเสริมอากาศที่สะอาดขึ้น ปอดมีสุขภาพดีขึ้น ส่งเสริมสุขภาพในภาพรวม นอกจากนี้ยังสามารถช่วยพัฒนาเครื่องวัดคุณภาพอากาศแบบพกพา งานวิจัยเกี่ยวกับแนวโน้มคุณภาพอากาศและดำเนินการศึกษาเพิ่มเติมถึงผลกระทบต่อสุขภาพของมลพิษทางอากาศชนิดต่าง ๆ รวมถึงผลกระทบต่อสุขภาพระบบทางเดินหายใจในระยะยาว

คำสำคัญ : สรีรวิทยาภูมิคุ้มกัน, ไมโครไบโอม, ฝุ่นละอองขนาดเล็ก PM 2.5, ภาวะเครียดที่เกิดจากออกซิเดชั่น

Introduction

Air pollution, including PM 2.5, is a major environmental and public health concern worldwide. It is primarily caused by human activities such as industrial emissions, transportation, power generation, and agricultural practices[1]. Thailand is one of the countries that face severe air pollution problems, particularly in urban areas and during certain seasons. The major sources of PM 2.5 in Thailand are vehicular emissions, industrial activities, construction, and biomass burning[2]. The health impacts of PM 2.5 exposure are significant and include respiratory problems, aggravated asthma, chronic obstructive pulmonary disease (COPD), chronic bronchitis, lung cancer and increased the risk of cardiovascular diseases[3,4].

Exposure to PM 2.5 can have significant effects on the immune response in the body. PM 2.5 to infiltrate deep into the respiratory system, presenting a significant risk to human health (5). Loss of balance in immune system can progress in many lung diseases (6). There are several ways of immune system encounters PM 2.5 particles, including inflammation, oxidative stress, immune system modulation, autoimmune diseases and susceptibility to infections[7,8]. The pulmonary immune system plays a pivotal role in defending the respiratory tract against invading pathogens and maintaining tissue homeostasis. However,

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elucidated the detrimental effects of PM 2.5 on the respiratory and cardiovascular systems[5,6], the intricate interplay between PM 2.5 exposure and the pulmonary immune system and lung microbiome is an area of increasing research interest.

In this context, investigating the effect of PM 2.5 on the pulmonary immune system and lung microbiome is vital to comprehend the underlying mechanisms by which air pollution impacts respiratory health. In this review, we explore the current state of knowledge regarding the intricate interplay between PM 2.5, the pulmonary immune system, and the lung microbiome, underscoring the importance of further research in this critical field of environmental health. This research may pave the way for knowledge strategies to mitigate the adverse effects of PM 2.5 exposure and contribute to the development of targeted interventions aimed at safeguarding respiratory well-being in the face of worsening air quality worldwide.

Global PM 2.5 effect on human health

PM 2.5, consisting of tiny particles with a diameter of 2.5 micrometres or less, is a major component of air pollution that poses a significant threat to human health. Due to its small size, PM 2.5 has the ability to penetrate deep into the respiratory system, reaching the lower airways and even crossing the alveolar barrier to enter the bloodstream[6]. Once inhaled, these particles can trigger a cascade of adverse effects on the respiratory system. One of the primary health implications of PM 2.5 exposure is its capacity to induce inflammation in the respiratory tract[12]. When PM 2.5 particles contact with lung tissues, they can activate immune cells, such as macrophages and neutrophils, to release pro-inflammatory cytokines[13]. This inflammatory response is an attempt by the immune system to clear the foreign particles from the lungs. However, chronic exposure to elevated PM 2.5 levels can result in persistent inflammation, leading to damage and remodelling of lung tissues over time[14]. This impaired lung function can manifest as reduced lung capacity and increased susceptibility to respiratory infections.

Moreover, PM 2.5 is known to generate reactive oxygen species (ROS) upon interaction with cells in the respiratory tract. ROS are highly reactive molecules that can cause oxidative stress, leading to cellular damage and dysfunction[15]. This oxidative stress further exacerbates the inflammatory response, creating a vicious cycle of immune system activation and tissue damage. The impact of PM 2.5 is not limited to the respiratory system alone. Studies have shown that these fine particles can enter the bloodstream and disseminate throughout the body, contributing to systemic inflammation and affecting other organs and systems[16,17]. The cardiovascular system is vulnerable to the adverse effects of PM 2.5 exposure[18]. The particles can promote atherosclerosis, the build-up of plaque in arterial walls, and increase the risk of cardiovascular diseases, including heart attacks and strokes[19].

Additionally, emerging research has pointed towards the influence of PM 2.5 on the lung microbiome, a diverse community of microorganisms that inhabit the respiratory tract[20]. Alterations in the lung microbiome composition due to PM 2.5 exposure can disrupt the delicate balance between beneficial and harmful bacteria, potentially exacerbating respiratory conditions and impairing local immunity[21]. Thus, PM 2.5 represents a formidable environmental hazard with far-reaching consequences for human health. Its ability to elicit inflammation, oxidative stress, immune dysregulation and lung microbiome system interfering.

Lung microbiome is a complex and diverse community of microorganisms that inhabit the respiratory tract. Traditionally, the lungs were believed to be sterile environments, but advances in sequencing technologies have revealed the presence of a vast array of bacteria, viruses, fungi, and other microorganisms in the lower respiratory tract[22]. The lung microbiome interacts dynamically with the host's immune system, influencing respiratory health and disease outcomes. There are many bacteria are identified in human lung including Streptococcus spp, Haemophilus influenzae, Prevotella spp., Veillonella spp., and Fusobacterium spp[23]. The composition and diversity of the lung microbiome can be influenced by various factors, including environmental exposures, such as air pollution and smoking, as well as the host's genetics, age, and overall health status[24]. Studies have shown that the lung microbiome of healthy individuals typically consists of a balanced and diverse microbial community, contributing to immune homeostasis and lung function maintenance[24].

One critical role of the lung microbiome is its involvement in immune modulation. The presence of beneficial microorganisms can stimulate the host's immune system, promoting a balanced and appropriate immune response to potential pathogens[25,26]. This interaction helps to prevent the overactivation of the immune system, which could lead to chronic inflammation and tissue damage[27,28]. Moreover, the lung microbiome serves as a protective barrier against pathogenic invaders[29].

By occupying niche spaces and competing for resources, beneficial microorganisms can limit the growth and colonization of harmful pathogens[30]. This "competitive exclusion" can be crucial in preventing infections and maintaining lung health. However, disturbances in the lung microbiome, known as dysbiosis, have been associated with various respiratory diseases[31]. Chronic respiratory conditions, such as asthma, COPD, and cystic fibrosis, have been linked to alterations in the lung microbiome composition. Dysbiosis can lead to an imbalanced immune response, impaired host-microbe interactions, and increased susceptibility to respiratory infections[32,33]. Furthermore, emerging evidence suggest that environmental factors, including air pollution, may impact the lung microbiome[4,32]. Exposure to fine particulate matter (PM 2.5) and other air pollutants has been associated with changes in the respiratory microbiota, potentially contributing to respiratory diseases and exacerbating existing conditions[34].

Thus, the lung microbiome plays a vital role in maintaining respiratory health and influencing immune responses within the respiratory tract. Its complex and delicate balance can be influenced by various factors, including environmental exposures, genetics, and overall health. Understanding the dynamics of the lung microbiome is crucial for advancing our knowledge of respiratory diseases and developing innovative approaches to promote lung health.

PM 2.5, lung immune cell and microbiome

1) Combustion-derived PM 2.5

The impact of combustion-derived PM 2.5 on lung health extends beyond its immediate respiratory effects, reaching into the intricate realm of lung immunopathology and the delicate balance of the lung microbiome as depicted in the Figure 1[9,35]. The toxic components of combustion-derived PM 2.5, such as polycyclic aromatic hydrocarbons (PAHs), heavy metals, and volatile organic compounds (VOCs), can elicit harmful immune responses and lead to immunopathological changes in the respiratory system[36]. Combustion-derived PM 2.5

particles can reach the deep lung tissues, where they contact with immune cells, such as macrophages and dendritic cells, as well as lung epithelial cells[37]. These immune cells recognize the foreign particles as threats and initiate an immune response to clear them from the lungs. However, chronic exposure to high levels of combustion-derived PM 2.5 can overwhelm the immune system and lead to immunopathology[38].

One of the primary immunopathological effects of combustion-derived PM 2.5 is the induction of persistent inflammation in the lungs. The particles contain pro-inflammatory substances, such as PAHs, that can activate immune cells, leading to the release of inflammatory cytokines and chemokines[39]. The sustained inflammation can cause tissue damage, disrupt lung function, and contribute to the development and exacerbation of respiratory diseases, such as asthma, chronic bronchitis, and chronic obstructive pulmonary disease (COPD)[37]. Moreover, the oxidative stress induced by combustion-derived PM 2.5 can also play a crucial role in lung immunopathology. The particles generate reactive oxygen species (ROS) when they encounter lung cells, leading to cellular damage and oxidative stress. The imbalance between ROS production and the body's antioxidant defences mechanisms can promote inflammation and further contribute to lung tissue injury[38]. In addition to inflammation and oxidative stress, combustion-derived PM 2.5 can impact the adaptive immune response in the lungs. The particles may act as adjuvants, enhancing the immune system's recognition of allergens and other environmental antigens[39]. This can lead to an exaggerated immune response, with the production of excessive levels of antibodies and immune cells, contributing to allergic reactions and respiratory hypersensitivity[40]. Furthermore, the ability of combustion-derived PM 2.5 to carry and release toxic components can alter the lung's immune microenvironment. The particles may adsorb and transport other pollutants and allergens into the respiratory tract, exacerbating immune responses and promoting immunopathology[41].

Recent studies have shown that exposure to combustion-derived PM 2.5 can lead to alterations in the composition and diversity of the lung microbiome. Chronic exposure to these fine particles may result in dysbiosis, an imbalance in the microbial community, and a shift in the relative abundance of certain microbial species. Dysbiosis induced by combustion-derived PM 2.5 can have several consequences for respiratory health[42]. Firstly, it may compromise the lung microbiome's protective functions. Beneficial microorganisms play a critical role in preventing the colonization of harmful pathogens by occupying niche spaces and competing for resources. When the balance of the microbiome is disrupted, the lung's natural defences mechanisms may weaken, making individuals more susceptible to respiratory infections[43]. Secondly, dysbiosis can influence the immune response in the respiratory tract. The lung microbiome interacts closely with the host's immune system, and alterations in the microbial community can lead to dysregulated immune responses[44]. The dysbiotic lung microbiome may contribute to an abnormal immune activation, promoting the release of pro-inflammatory cytokines and chemokines, and sustaining inflammation in the respiratory tract[45]. Moreover, the gut-lung axis, a bidirectional communication pathway between the gut microbiome and the lung, plays an essential role in lung health. Disruptions in the lung microbiome caused by combustion-derived PM 2.5 exposure can impact the gut-lung axis, leading to gut dysbiosis and systemic inflammation, which may further exacerbate respiratory conditions[46]. Furthermore, the

exacerbate respiratory conditions[46]. Furthermore, the alterations in the lung microbiome induced by combustion-derived PM 2.5 can also affect the metabolism and breakdown of the particles within the respiratory tract[11]. Beneficial microorganisms may possess enzymatic capabilities that can modify or degrade certain components of PM 2.5, potentially influencing their persistence and toxicity in the lungs. Dysbiosis may impair these metabolic processes, leading to prolonged exposure to harmful pollutants and increased damage to lung tissues.

2) Secondary PM 2.5 compounds

Secondary PM 2.5 is formed by chemical reactions of atmosphere gases with solid and liquid particles including particles from oil refining and pulp and paper industrial production process. One of the keyways in which secondary PM 2.5 impacts lung immunophysiology is by triggering inflammation in the respiratory tract as illustrated in the Figure 1. The particles contain chemical components that can activate immune cells, such as macrophages and dendritic cells. These immune cells recognize the foreign particles as threats and initiate an immune response to remove them from the lungs. However, chronic exposure to secondary PM 2.5 can lead to persistent immune activation, resulting in the continuous release of pro-inflammatory cytokines and chemokines[9]. The sustained inflammation in the lungs caused by secondary PM 2.5 can lead to tissue damage, disrupt lung function, and contribute to the development or exacerbation of respiratory diseases, such as asthma, chronic bronchitis, and COPD[6]. Moreover, the chronic inflammatory state may also affect the lung's immune microenvironment, influencing the balance of immune cell populations and altering immune responses. Additionally, secondary PM 2.5 can modulate the adaptive immune response in the respiratory tract[47]. The particles may act as adjuvants, enhancing the immune system's recognition of allergens and other environmental antigens[48]. This can lead to an exaggerated immune response, with the production of excessive levels of antibodies and immune cells, contributing to allergic reactions and respiratory hypersensitivity[49]. Furthermore, the ability of secondary PM 2.5 to generate oxidative stress is also relevant to lung immunophysiology. The fine particles can produce reactive oxygen species (ROS) upon contact with lung cells, leading to cellular damage and oxidative stress[49]. The ROS generated by secondary PM 2.5 can activate immune cells and trigger inflammation, further exacerbating immunological responses in the respiratory tract[15].

Studies have shown that exposure to secondary PM 2.5 can lead to alterations in the composition and diversity of the lung microbiome. Chronic exposure to these fine particles may result in dysbiosis, an imbalance in the microbial community[9,35], and a shift in the relative abundance of certain microbial species. Dysbiosis induced by secondary PM 2.5 can have several implications for respiratory health including mucus production and clearance, infection susceptibility, ROS generation and increasing in bacterial resistance[15,47-49].

3) Dust and soil particle PM 2.5

Crustal PM 2.5 can have various effects on lung immunophysiology, influencing the respiratory immune response and potentially leading to adverse respiratory health outcomes as presented in the Figure 1[50]. One of the keyways in which crustal PM 2.5 impacts lung immunophysiology is through its ability to trigger inflammation in the respiratory tract[51]. These particles can carry pro-inflammatory substances and antigens, such as endotoxins and allergens, which can activate immune cells in the lungs[50]. The activated immune cells, such as macrophages

and chemokines, leading to an inflammatory response. Chronic exposure to crustal PM 2.5 can result in sustained inflammation in the respiratory tract, which may contribute to tissue damage and remodelling of the airways. Moreover, crustal PM 2.5 can also influence the adaptive immune response in the lungs[52]. The particles can act as adjuvants, enhancing the immune system's recognition and response to allergens and other environmental antigens. This can lead to an exaggerated immune response, with the production of excessive levels of antibodies and immune cells, potentially promoting allergic reactions and respiratory hypersensitivity[53].

Furthermore, crustal PM 2.5 particles can exacerbate pre-existing respiratory conditions, such as asthma and chronic bronchitis. Individuals with these conditions are particularly susceptible to the adverse effects of crustal PM 2.5 exposure. The particles can trigger acute exacerbations of these conditions, leading to worsening symptoms, increased hospitalizations, and reduced quality of life for affected individuals[54]. Additionally, crustal PM 2.5 may have specific effects on the lung's mucosal immune system. The particles can impact the integrity of the respiratory epithelial barrier, making it more permeable to pathogens and other particles[55]. This disruption of the mucosal barrier can compromise the lung's first line of defences against respiratory infections, increasing susceptibility to viral and bacterial respiratory diseases[56].

Limited studies have begun to explore the effects of crustal PM 2.5 on the lung microbiome. Exposure to these particles may lead to alterations in the composition and diversity of the lung microbial community[57]. Chronic exposure to crustal PM 2.5 may result in dysbiosis, an imbalance in the relative abundance of certain microbial species[58].

4) Biological PM 2.5

One of the primary ways in which biological PM 2.5 impacts lung immunophysiology is through its role in triggering allergic responses as indicated in the Figure 1. Pollen and fungal spores are common sources of biological PM 2.5 and can act as potent allergens[59]. When inhaled, these particles can activate immune cells, such as mast cells and eosinophils, leading to the release of histamine and other inflammatory mediators[60]. This can cause allergic reactions in the respiratory tract, leading to symptoms such as sneezing, coughing, wheezing, and shortness of breath. Moreover, some biological PM 2.5 particles, such as bacteria and viruses, can directly interact with immune cells in the lungs. Bacteria and viruses may invade lung tissues and infect immune cells, leading to acute respiratory infections. In response, the immune system mounts an immune response to combat the infection, resulting in inflammation in the respiratory tracts[61,62]. The immunophysiological effects of biological PM 2.5 are not limited to the respiratory tract alone. These particles can also impact systemic immune responses. For example, certain bioaerosols can enter the bloodstream and disseminate throughout the body, influencing immune function beyond the respiratory system[62]. Furthermore, the composition and abundance of biological PM 2.5 can vary with the seasons and environmental conditions(62). During specific times of the year, such as pollen seasons or mold spore release, the concentration of biological PM 2.5 in the air may significantly increase[63]. This heightened exposure to bioaerosols can exacerbate allergic responses and increase the risk of respiratory infections, particularly in individuals with pre-existing respiratory conditions[64].

Limited studies have begun to explore the impact of biological PM 2.5 on the lung microbiome. Exposure to these bioaerosols may lead to alterations in the composition and diversity of the microbial community in the respiratory tract[65]. Dysbiosis

community in the respiratory tract[65]. Dysbiosis induced by biological PM 2.5 can have several implications for respiratory health. Additionally, some bioaerosols, such as bacteria and fungi, may possess enzymatic capabilities that can modify or degrade certain components of PM 2.5 particles[66]. Dysbiosis induced by biological PM 2.5 may impair these metabolic processes, potentially influencing the persistence and toxicity of PM 2.5 particles in the lungs[67].

5) Biomass and wildfire burning PM 2.5

The fine particles from biomass and wildfire burning can also carry biological materials, such as endotoxins and allergens, which can further amplify the immune response as demonstrated in the Figure 1. These biological components can trigger allergic reactions and exacerbate respiratory hypersensitivity, particularly in individuals with pre-existing allergies[67]. Additionally, exposure to biomass and wildfire burning PM 2.5 can impair the lung's innate immune defenses. The particles can interfere with the function of immune cells, such as macrophages and dendritic cells, that play a crucial role in recognizing and clearing pathogens from the lungs[68]. This impairment of the innate immune response may compromise the lung's ability to defend against infections and other environmental threats[68]. Furthermore, biomass and wildfire burning PM 2.5 can generate oxidative stress in the respiratory tract[69]. The particles contain reactive species, such as PAHs, that can produce reactive oxygen species (ROS) upon contact with lung cells[70]. The excessive production of ROS overwhelms the body's antioxidant defense mechanisms, leading to oxidative damage to cellular structures and further exacerbating the inflammatory response[71].

Limited research has explored the specific effects of biomass and wildfire burning PM 2.5 on the lung microbiome. However, it is plausible that exposure to these fine particles may lead to alterations in the composition and diversity of the lung microbiome resulting in dysbiosis and imbalance in the microbial species[5,72].

6) Sea salt aerosol PM 2.5

Sea salt aerosols can reach the lower respiratory tract, where they can interact with immune cells and lung tissues. The primary component of sea salt aerosols is sodium chloride (NaCl), which is relatively inert[73]. However, studies have shown that sea salt aerosols can modulate immune responses and affect lung immunophysiology through several mechanisms shown in Figure 1 as well. One significant effect of sea salt aerosols on lung immunophysiology is their ability to trigger inflammation in the respiratory tract[74,75]. While NaCl is not inherently inflammatory, sea salt aerosols can act as carriers for other bioactive substances present in the atmosphere. For example, sea salt particles can adsorb pollutants and allergens, such as nitrogen oxides (NOx) and pollen, onto their surfaces[76]. These particles can activate immune cells, such as macrophages and dendritic cells, leading to the release of pro-inflammatory cytokines and chemokines[77]. This can result in localized inflammation in the lungs, contributing to respiratory symptoms and exacerbation of respiratory conditions, especially in individuals with pre-existing respiratory diseases[77]. Sea salt aerosols can also impact the immune system by affecting the mucosal barrier function in the respiratory tract. The aerosols can alter the epithelial barrier's integrity, making it more permeable to pathogens and other particles. This disruption of the mucosal barrier can compromise the first line of defense against respiratory infections, increasing susceptibility to viral and bacterial respiratory diseases[78,79]. Furthermore, sea salt aerosols may influence the activation and

suggested that exposure to and associated cytokines [80,81]. Th17 cells are a subset of T helper cells with defined by their secretion of pro-inflammatory interleukin 17 (IL-17). Th17 cells are involved in inflammation and have been implicated in the pathogenesis of various respiratory diseases, including asthma and COPD[82]. This immunomodulatory effect of sea salt aerosols may contribute to the development or exacerbation of these respiratory conditions.

Studies on the effects of sea salt aerosol PM 2.5 on the lung microbiome are limited, but it is plausible that exposure to these particles may have implications for the microbial community in the respiratory tract[83]. The inorganic salts in sea salt aerosols may create an environment that influences the growth and survival of microorganisms, potentially altering the lung microbiome's composition and diversity[84]. Moreover, the microbial components carried by sea salt aerosols can directly impact the lung microbiome. Bacteria and viruses from the sea surface can enter the respiratory tract upon inhalation and interact with the existing microbial community[85]. Depending on the specific microbial species present, this interaction may lead to alterations in the lung microbiome's composition and function. The effects of sea salt aerosol PM 2.5 on the lung microbiome may have consequences for respiratory health[86]. The lung microbiome plays a critical role in maintaining lung homeostasis and protecting against respiratory infections. Disruptions in the microbial community can compromise the lung's defence mechanisms, potentially increasing the susceptibility to respiratory diseases[5]. However, the influence of sea salt aerosol PM 2.5 on the lung microbiome is likely to be context-dependent. Factors such as individual health status, underlying respiratory conditions, and the coexistence of other air pollutants may modulate the effects of sea salt aerosols on the lung microbiome[87].

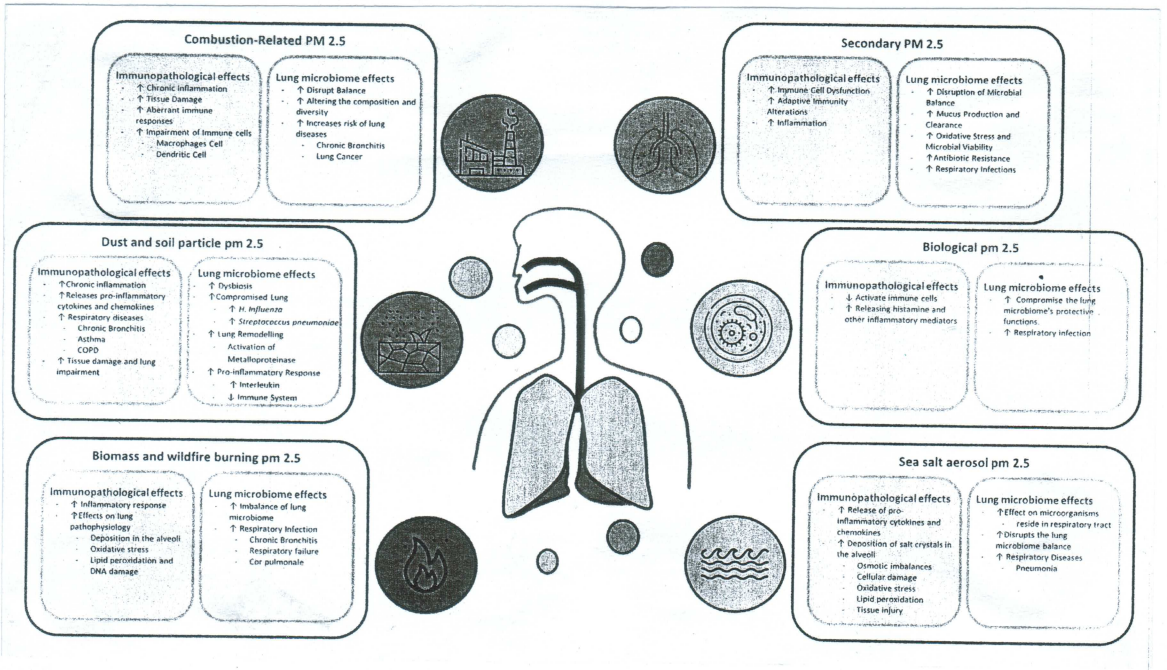

Figure 1 The effects of PM2.5 on human immunopathology and human microbiome. The figure presents important effect of each type of particulate matter (PM) exposure on immunopathology and microbiome in the respiratory system.

Conclusion

In conclusion, the intricate relationship between PM 2.5 and its diverse sources and their impact on the lung's immunophysiology and microbiome underscores the critical importance of understanding the multifaceted nature of air pollution's effects on respiratory health. Particulate matter, especially PM 2.5, is not a uniform entity but a complex mixture originating from various anthropogenic and natural sources. Each type of PM 2.5 carries distinct chemical compositions and biological components that interact with the respiratory immune system and the lung microbiome in unique ways. The immunopathological effects of PM 2.5 involve triggering inflammation, oxidative stress, and immune dysregulation in the respiratory tract. These effects can lead to a spectrum of respiratory disorders, from acute exacerbations to chronic diseases, affecting individuals' quality of life and imposing a considerable burden on public health systems. Similarly, PM 2.5 can significantly influence the lung microbiome, disrupting its equilibrium and compromising its protective and regulatory functions. Dysbiosis induced by PM 2.5 exposure may leave the respiratory tract more vulnerable to infections and exacerbate existing respiratory conditions. Moreover, further research is imperative to delve deeper into the nuanced interactions between different types of PM 2.5, the immune system, and the microbiome. This knowledge can pave the way for targeted interventions, therapies, and preventive measures that could enhance the lung's resilience against the adverse effects of PM 2.5 exposure. Preventing the long-term health effects of PM 2.5 exposure on different populations, including vulnerable groups such as children, the elderly, and individuals with pre-existing health conditions by avoiding assessing the indoor and outdoor environments, workplaces, and transportation. Moreover, risk assessment findings to inform the development of air quality standards and regulations aimed at reducing PM2.5 levels and protecting public health still legal need including industrial activities, transportation, and residential combustion to reduce PM 2.5 exposure and protecting vulnerable populations from the adverse effects of air pollution.

Declaration of use of AI in the writing process

In this scientific reviewed work, generative artificial intelligence (AI) has been used. Statement: The author(s) used ChatGPT during the preparation of this work to generate the concept and the overviewed planning. After utilizing the tool/service, the author(s) thoroughly reviewed and edited the content as necessary and assumed full responsibility for the publication's content.

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