Respirable Coal Mine Dust: A Review of Respiratory Deposition, Regulations and Characterization

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Abstract: In the late 1990s, despite years of efforts to understand and reduce coal worker’s pneumoconiosis (CWP) prevalence from more than 30% in 1970 to less than 4.2%, the level of occurrence among the US coal miners increased unexpectedly. The recent resurgence of lung diseases has raised concerns in the scientific and regulatory communities. In 2014, the United States Mine Safety and Health Administration (MSHA) issued a new dust rule changing the respirable coal mine dust (RCMD) exposure limits, measurement technology, and sampling protocol. The analysis for probable causes for the substantial increase in the CWP incidence rate is rather complicated. This paper aims to conduct a review of RCMD respiratory deposition, health effects, monitoring, regulations, and particle characteristics. The primary sources of RCMD along with the health risks from potential exposure are highlighted, and the current RCMD exposure regulations of the major coal producer countries are compared. A summary of RCMD characterization studies from 1972 to the present is provided. A review of the literature revealed that numerous factors, including geological and mining parameters, advancements in mining practices, particle characteristics, and monitoring approaches are considered to contribute to the recent resurgence of RCMD lung diseases. However, the root causes of the problem are still unknown. The effectiveness of the new dust rules in the United States will probably take years to be correctly assessed. Therefore, future research is needed to understand the relationship between RCMD particle characteristics and lung deposition, and the efficacy of current monitoring practices to measure the true dose of RCMD exposure.

Keywords: respirable coal mine dust; lung deposition; coal dust characteristics; exposure limits and regulations; respiratory diseases; occupational health

1. Introduction

Dust, as an inherent byproduct of mining, may impose various health and safety issues in mining operations. The term dust is used for solid particles in the air and is defined as airborne particles, usually in a size range of 1 to 100μm [1,2]. Mineral clouds of dust generally occur when collisions, abrasions, cutting, crushing, and explosions break down rocks [3–5]. Such mechanical and chemical processes generate dust particles in various sizes, typically formed in irregular shapes [4,6,7]. Generally, the amount of dust generated during excavation is estimated to be approximately 3% of the total mass of the excavated materials [8]. The chance of a dust particle to deposit in the human respiratory system depends significantly on particle size or aerodynamic diameter (defined as the diameter of a unit density particle (1 g/cm³) with the similar settling velocity of the particle) [9–12].
Respirable dust generally refers to particles having an aerodynamic diameter < 10 μm and a median cut-point (d50) of 4 μm [13–15].

The United States Mine Safety and Health Administration (MSHA) states that “Any respirable dust in the mine atmosphere is considered respirable coal mine dust to which miners are exposed and, when measured, is counted for determining compliance with the respirable dust standard” (79 Fed. Reg. 24,866). It is estimated that 40–95% of respirable coal mine dust (RCMD) in the underground coal mine is pure coal and the rest contains particles generated from cutting the roof and floor, diesel equipment, rock dusting practices, etc. [16–18]. Dust generation depends on geological parameters and technical factors. Geological parameters include coal thickness, composition, cleavage, compactness, hardness, volatile matter, ash, and coal moisture content. Mining methods, cutting height, cutting equipment, and type and condition of cutting bits are among the contributing technical factors [8,19]. The primary sources of RCMD have been found to be coal seam and surrounded rock strata, intake air, diesel exhaust, mining operations, and rock dusting (Figure 1) [7,20–25]. The concentration of dust depends on the number of factors, including types of activity, the number of free surfaces in the cross-section walls, ventilation, and dust control practices.

![Figure 1. Major sources of RCMD in underground coal mines [16,17,26].](image)

Cumulative inhalation of RCMD can lead to severe lung diseases, including coal worker’s pneumoconiosis (CWP), silicosis, mixed dust pneumoconiosis, dust-related diffuse fibrosis (DDF), and progressive massive fibrosis (PMF) [27–29]. Black lung or CWP has been considered as a main concern among US coal workers since 1962 that followed by regulations to decrease the limits of dust exposure once in a while. In general, the regulations resulted in a significant decrease in the progression of respiratory lung diseases as well as the number of reported CWP cases by the late 1990s [11]. However, an unexpected increase in the number of CWP cases was reported in the late 1990s that were more chronic (Figure 2). Since the time of the disease to manifest is at least five years and can be latent to 10–30 years, the trend for CWP progression in the United States was descending to one-sixth of the earlier percentage in 2000. Since 2000, the trend started to change during mid-2010s, noting that recent CWP cases were more severe.

A considerable amount of research and analysis has investigated the root causes of the increase in lung diseases [7,10,29–42]. Nevertheless, identifying the leading causes of this drastic rise seems to be difficult. This paper provides a review of literature on RCMD penetration in the respiratory system and lung deposition, subsequent health problems, exposure limits and regulations, monitoring, and characterization techniques and particle characteristics. The current gaps in knowledge and future research needs are highlighted, and the importance of understanding the relationship between RCMD characterization and lung depositions are discussed.
2. Respirable Dust Deposition in the Human Respiratory System

A simplified schematic of the human respiratory system is shown in Figure 3. When breathing in, air flows through the nostrils and enters the nasal cavity, where, at the entrance, nose hairs coated with mucus are able to trap large particles of dust [43,44]. The main nasal airway (turbinate) assists to warm and moisturize the inhaled air before entering into the lung [43,45,46]. Once passing through the nasal airway, the inhaled air penetrates through the oropharynx, larynx, trachea, and then enters the lungs. The point where the inhaled air splits into the two mainstem bronchi is called the carina [44,45,47]. The right mainstem bronchus is wider and more vertical (and divides into three lobes or bronchi) than the left lung, which divides into two lobes bronchi [48–51]. The trachea and first three generations of bronchi are large airways, lined mostly by ciliated columnar cells and a handful of goblet cells that secrete mucus, helping to trap particles [44,52]. The ciliated columnar cells beat rhythmically together to move the mucus and any trapped particles from the air towards the pharynx, where they can be either spit out or swallowed, i.e., the mucociliary clearance mechanism [43,52,53].

After the first three generations of bronchi, the air passes through smaller bronchioles for 15–20 generations; the first 16 branching in the tracheobronchial (TB) region and the remaining in the alveolar region [47,48,54]. These conducting bronchioles receive oxygen from the bronchial arteries where the walls are similarly lined by ciliated columnar cells and mucus-secreting goblet cells [52,53]. These cells secrete glycosaminoglycan, a material that protects the bronchiolar or epithelium by helping to regenerate and replace damaged cells [52,53]. Eventually, the respiratory bronchioles end where there are millions of alveoli in the gas exchange region [50,54–57]. This is the final destination of the inhaled air, in which the wall is lined by thin epithelial cells called pneumocytes [48,52]. If a particle makes it deep into the lungs, there are alveolar macrophages that can swallow and move up the particle to the conducting bronchioles (slow phase of mucociliary clearance) [44,48].

There have been few reports that investigate the effect of physicochemical properties of coal dust including morphology and particle shape, size, composition, and functional groups on CWP [58]. Furthermore, several studies documented that nano-size coal particles are more toxic owing to their special physicochemical properties and ease of absorption by living organisms. These nanosized particles can also be suspected of having a significant contribution to the lung diseases [58–60]. In addition to the size of particles, the shape, in another word, angularity and sphericity, will significantly affect the respiratory...
deposition. For instance, the total deposition of μm-sized fibers and submicron oblate disks was found significantly higher for non-spherical particles compared to spherical particles [61,62]. In general, angular edges increase the inflammation since they can penetrate into the lung tissue. Those particles that contain toxic elements (e.g., Fe, Cd, Hg, Pb) are going to be dangerous if eventually enter into the blood stream. Detailed studies on the relation between particle shape and toxicity revealed that angular particles such as fibers, which have more roughness and sharp edges, have higher risk of toxicity compared to spherical particles [21,58,60].

There are a variety of mechanisms for particle deposition in the respiratory system, some depending on particle size. To illustrate the respiratory deposition of a particle based on its size, the human respiratory system can be simplified in three regions: the head region, the tracheobronchial region (TB), and the alveolar region (gas exchange region) [63–68]. Particles with an aerodynamic diameter of less than 100 μm are inhalable through the nasal and oral cavities in the head region. After entering into the respiratory system, large particles with large inertia may be trapped in the upper airways, while smaller particles with small inertia move along with the air and enter the lower airways [1,43,51,55,69,70]. The inhaled particles that fail to deposit in the respiratory system will be exhaled [42,44,48,58–66,70]. RCMD particles may include a considerable amount of fine or ultrafine particles from which the most damaging particles are probably those that are small enough to penetrate deep into the lungs. In light of this, diesel particulate matter (DPM) with a diameter of less than 1 μm is considered a concern for underground workers. Submicron particles are not cleared as efficiently as larger particles and have mobility within the respiratory system or beyond via translocation to blood [47,59].

The probability of particle deposition in different regions of the respiratory system as a function of the particle’s aerodynamic diameter is demonstrated in Figure 3. [43]. Almost all small particles (less than 10 nanometers in diameter) and more than 75% of large particles (10 micrometers in diameter) are inhalable, out of which roughly 20% of small particles and nearly all of the large particles are deposited in the head region. Total deposition in the TB region is relatively low. In this region, approximately 25% of small particles and 1.5% of large particles are deposited. The deposition of medium-size particles (300 nanometers in diameter) is higher if not already deposited in the head region. Near 42% of small and about 2% of large particles are deposited in the alveolar region [43,71–73]. A summary of lung deposition studies is presented in Table 1.
3. RCMD Exposure Health Risks and Global Disease Distribution

Exposure to RCMD may affect both human internal and external organs. These health effects include eye opacities, hearing loss, contagious illnesses, lung diseases, kidney diseases, cardiovascular problems, nervous system damage, and voice and skin disorders (Figure 4). Despite its effects on other vital organs, cumulative exposure to RCMD is well-known to result in obstructive pulmonary diseases, which are chronic, vulnerable, progressive, and possibly fatal [74–76]. In the United States, from 1995 to 2004, pneumoconiosis in coal miners resulted in more than 10,000 mortalities (79 Fed. Reg. 85, May 1, 2014). Pneumoconiosis was first defined by the British National Insurance (Industrial Injuries) Act in 1946 as “fibrosis of the lungs due to silica dust, asbestos dust or other dust and includes the condition known as dust retention.” [77]. The American Lung Association defines pneumoconiosis as a group of interstitial lung disease caused by overly breathing in dust particles that damage lungs tissues by scarring and finally impairing the ability to breath. Pneumoconiosis can be categorized as simple or complicated forms. The simple form called coal workers’ pneumoconiosis, or CWP, causes small scars in the lung tissue, while the complicated form presents with huge amount of scarring tissue known as progressive massive fibrosis, or PMF [78]. Based on the composition of the inhaled dust (i.e., organic and inorganic contaminants with known pro-inflammatory and carcinogenic properties such as coal, silica, iron, cadmium, lead, kaolin, and pyrite), and the exposure duration, different stages of CWP and severity, including pulmonary hypertension, cor pulmonale (defined as an alteration in the structure and function of the right ventricle (RV) of the heart caused by a primary disorder of the respiratory system), and death, may manifest with miscellaneous symptoms [19,38,79]. For either simple or complicated forms of pneumoconiosis, the injury involves the destruction of blood vessels and air sacs in the lungs. The scarring tissue becomes thick and stiff in a way that makes breathing strictly formidable. This is considered an interstitial pulmonary disease that mainly includes asbestosis, silicosis, fibrosis, and black lung or CWP.
Determining the interstitial lung disease (ILD) (i.e., a group of disorders that cause progressive scarring of lung tissue) in coal workers exposed to RCMD seems to be a complicated investigation. Most experiments have shown a robust dose-response in the relationship between RCMD and ILD. However, dose-response for pure coal dust has not been ruled-out [12,79]. Most of the investigations focus on studies that indicate that non-mineral coal dust has an independent impact on ILD progress [12,31,86,87]. Many of those tests were cross-sectional studies, with exposures to quartz to some extent, and a few studies have investigated the effect of smoking and age [12,86,88]. Brown et al. [6] provided an analysis of the thoracic and respirable fractions according to the three variables of age, sex, and activity level (light, moderate, and heavy) that affect the tidal volume (which is the lung volume representing the normal volume of air displaced between normal inhalation and exhalation when extra effort is not applied. In a healthy, young human adult, tidal volume is approximately 500 mL per inspiration or 7 mL/kg of body mass). This study predicted that an increase in activity intensity and airflow causes the impaction of particles with a greater cut-point range of aerodynamic diameter into the ET fraction. In addition to this estimation, [10] presented the thoracic and respirable fractions of ~3 μm in adults (female slightly less than male), while in children, these fractions were estimated as 5 μm and 4 μm, respectively [10].

<table>
<thead>
<tr>
<th>Authors</th>
<th>Proposed Model</th>
<th>Methodology</th>
<th>Results</th>
</tr>
</thead>
</table>
| Brown et al. [10]| Modifications to International Commission on Radiological Protection (ICRP) model | Experimental and mathematical modeling based on the ICRP human respiratory model | - Heavy activities and mouth breathing increase thoracic and respirable fraction for inhaled particles  
- For moderate activities, a 50% cut-points for particle penetration past (i.e., P(ET)avg) is estimated to be ~3 μm in adults and ~5 μm in children. The cut-points for P(TB)avg are slightly less than 3 μm in adults and slightly greater than 4 μm in children. |
| Ghalati et al. [46] | Computational model                                                                 | Lagrangian and Eulerian models                                              | - Increasing the particles diameter and flow rate lead to increase in particle deposition of micron-size particle and decrease in nano-size particle’s deposition fraction                                                                 |
The Brownian motion of nanoparticles leads to their rather uniform diffusion, in contrast to the regional deposition pattern of micron-size particles, which is highly dependent on particle inertia. The local deposition fractions proved that the nasal cavity play a significant role in filtering large micron-size particles and very small nano-size particles.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Methodology</th>
<th>Simulation</th>
<th>Global Distribution of RCMD Lung Diseases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rahimi-Gorji et al. [49]</td>
<td>Laminar-to-turbulent airflow, transport and deposition of micro-particles was performed by Eddy Interaction Model (EIM) from the oral cavity up to generation G6 by two-phase flow simulation</td>
<td>-</td>
<td>Owing to the lack of reliable statistics, estimation of the global prevalence of lung diseases related to coal mine dust is difficult. In developing nations, where job practices are not well regulated, the incidence rate is expected to be higher. RCMD lung diseases have deteriorated with tightly imposed restrictions on dust control in developed countries [23]. The frequency and intensity of RCMD lung diseases over the last 20 years have resurged in several nations [8,23,92,93]. In the United States, this trend declined to 2.1% in the 1990s, then unexpectedly increased (to 3.2%) in the late 1990s [11,23]. Each year in China, on average, 10,000 patients employed in coal mines are added to the list of pneumoconiosis patients, and over 2500 miners die from this disease [8,94,95]. There were 122,333 new cases of pneumoconiosis reported between 1997 and 2009, ~44% of which were due to CWP, showing that its prevalence remained high (around 6.02%) [93]. In Germany, about 300 new compensated cases per year reported by 1994, which showed severe CWP mostly in retired coal miners [96] Among occupational diseases in Poland, the number of cases reported in coal mining (76.6% of those cases are CWP) is more than three times of other industries [8,34]. By 2017, the total number of pneumoconiosis cases reported was 7340, 80% of which were active and former employees of hard coal mines [8].</td>
</tr>
</tbody>
</table>
In Australia, between 1979 and 2002, 6% of total mining fatalities were classified as CWP, with the number of fatalities decreasing steadily over time [92,97]. Similarly, in India, the resurgence of pneumoconiosis in coal miners is relatively high [19,93]. In the United Kingdom, the incidence of CWP declined dramatically between 2004 and 2008 and has remained relatively stable since then [98].

4. RCMD Exposure Limits and Regulations in the Major Coal Producer Countries

RCMD is mainly regulated by reducing the exposure duration and the total mass of RCMD in the working areas [11,28,37,79]. However, RCMD exposure limits and regulations vary in different countries. While the record of occupational disease recognition goes back to 1706 [99], revealing the first case of CWP in a Scottish coal mine in 1831, stimulating other nations to regulate RCMD concentration in underground coal mines [100], the lack of occupational disease monitoring and medical knowledge and equipment caused the late attention of coal-producing countries to recognize CWP cases. For example, the first case of CWP in the United States was revealed during the 1920s, China in 1949, India in 1956, Poland in 1966, and Germany in 1974 [8,19,23,97,99,101]. The major coal producer countries (shown in Table 2 commenced with setting regulations for RCMD exposure limits (listed in Table 2).

In 2018, China produced approximately 3,500 million tones (Mt) of coal as the top coal producer, of which 90% is extracted from underground mines [23,102,103]. Interestingly, the permissible exposure limits of total dust in China varies between 2 mg/m$^3$ to 20 mg/m$^3$ (1 mg/m$^3$ for coal with 50% silica content to 6 mg/m$^3$ coal with 5% silica content [23,95]). India, in second place, produced 764 Mt with only 10% from underground mines [19,23,102,103]. The maximum exposure limit (MEL) is 3 mg/m$^3$ when respirable crystalline silica (RCS) in respirable dust is less than 5%. However, if free silica is greater than 5%, then MEL should be determined by 15/(% RCS) [23,104]. The regulations in the United States, as the third coal producer, is discussed below in detail. Australia in the fourth place produced 502 Mt, which only 20% of coal mines are underground mines [23,102,103]. The exposure limit in Australia is 1.5 mg/m$^3$ for coal with silica content less than 5% in general [105]. South Africa produced 257 Mt, 50% of which was from underground coal mines. In South Africa, the RCMD concentration limit is set to 2 mg/m$^3$ for coal with less than 5% silica content [23,102,103,106].

In the United States, the setting of regulations on occupational diseases has nearly always led to a prolonged controversy among conflicting interests [23,34,107]. The manifestation of black lung disease was in the 1960s when 30% of workers who had more than 25 years of tenure in underground coal mines were diagnosed with CWP [23]. Since then, considerable medical treatment efforts have been implemented, while no certain cure for CWP has been achieved [28]. Therefore, the effort has been to reduce the number of lung disease incidents by alleviating the exposure of RCMD in working areas. In 1969, the very first RCMD concentration limit of 3.0 mg/m$^3$ coal dust concentration was introduced and was lowered to 2.0 mg/m$^3$ with crystalline silica or quartz less than 5% in 1972. The black lung disease trend from the 1970s to the late 1990s significantly declined. In 1995, the National Institute for Occupational Safety and Health (NIOSH) recommended that the permissible exposure limit (PEL) should be lowered to 1 mg/m$^3$ for RCMD and 0.05 mg/m$^3$ for silica concentration. This was followed by the 2014 (effected on 1 August, 2016) MSHA dust rule, in which the PEL was lowered to 1.5 mg/m$^3$ for RCMD and 0.1 mg/m$^3$ for quartz, along with changes in sampling technique and duration [23].

Previous studies indicated that CWP prevalence is related to the exposure of RCMD to coal workers. CWP can even effectively progress among coal workers after exposure removal [1,2,4,108]. The risk of CWP prevalence is associated with RCMD composition, concentration, and exposure duration [4,22,109]. Doney et al. [74,110] investigated the mass concentrations of RCMD and RCS using the MSHA database between 1982 and 2017. The results of 681,497 RCMD and 210,944 respirable silica dust (RCS) samples in underground mines showed an average of 0.55 mg/m$^3$ and 0.038 mg/m$^3$ for RCMD and RCS.
concentrations, respectively. However, in surface mines, the average values were 0.17 mg/m$^3$ and 0.02 mg/m$^3$, respectively. The number of RCMD samples exceeding the PEL in underground mines was three times greater than surface mines. The geometric mean of RCMD for different occupational group in underground coal mines was reported as longwall worker (1.02 mg/m$^3$), continuous miner operator and helper (0.73 mg/m$^3$), cutting machine operator and helper (0.67 mg/m$^3$), auger (0.65 mg/m$^3$), roof bolter (0.59 mg/m$^3$), stopping builder/ventilation man/mason (0.57 mg/m$^3$), blaster and helper (0.50 mg/m$^3$), coal drill operator and helper (0.48 mg/m$^3$), beltman/conveyor man/belt cleaner (0.46 mg/m$^3$), and loading machine operator (0.44 mg/m$^3$) [74,110].
Table 2. Top 10 coal producers in the world with a dust exposure limit.

<table>
<thead>
<tr>
<th>Country</th>
<th>Production Ranking (% of World Production)</th>
<th>Production Ranking</th>
<th>Underground/Surface Seam Properties</th>
<th>Coal Type</th>
<th>Thickness</th>
<th>Common Underground Mining Method</th>
<th>Regulation Year</th>
<th>Dust Exposure Limits</th>
<th>Silica Content PEL (mg/m³ or %)</th>
<th>Sampling</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>1 (45.2%)</td>
<td>90% U 10% S</td>
<td>75% bituminous 20% anthracite</td>
<td>Deep thick</td>
<td>LW</td>
<td>2002</td>
<td>2.5</td>
<td>4</td>
<td>&lt;10%</td>
<td>PGS</td>
<td>[23], [94], [95]</td>
</tr>
<tr>
<td>India</td>
<td>2 (9.9%)</td>
<td>90% S 10% U</td>
<td>anthracite bituminous</td>
<td>thick short deep</td>
<td>R&amp;P</td>
<td>1987</td>
<td>2</td>
<td>10/(% silica)</td>
<td>&lt;5% &gt;5%</td>
<td>Indian Device</td>
<td>[23], [19]</td>
</tr>
<tr>
<td>United States</td>
<td>3 (8.9%)</td>
<td>73% S 27% U</td>
<td>bituminous sub-bituminous</td>
<td>thin</td>
<td>R&amp;P</td>
<td>2016</td>
<td>1.5</td>
<td>-</td>
<td>0.1 mg/m³</td>
<td>PGS</td>
<td>[23]</td>
</tr>
<tr>
<td>Australia</td>
<td>4 (6.5%)</td>
<td>80% S 20% U</td>
<td>anthracite bituminous sub-bituminous</td>
<td>thick</td>
<td>90% LW</td>
<td>2020</td>
<td>1.5</td>
<td>-</td>
<td>0.05 mg/m³</td>
<td>PGS</td>
<td>[105]</td>
</tr>
<tr>
<td>Indonesia</td>
<td>5 (6.2%)</td>
<td></td>
<td>Not available at the time of the review.</td>
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<tr>
<td>Russia</td>
<td>6 (5.4%)</td>
<td></td>
<td>Not available at the time of this review.</td>
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<tr>
<td>South Africa</td>
<td>7 (3.3%)</td>
<td>51% U 49% S</td>
<td>sub-bituminous bituminous anthracite</td>
<td>relatively thin</td>
<td>90% R&amp;P</td>
<td>1997</td>
<td>2</td>
<td>-</td>
<td>&lt;5%</td>
<td>PGS</td>
<td>[23], [106]</td>
</tr>
<tr>
<td>Germany</td>
<td>8 (2.2%)</td>
<td>3% U</td>
<td>bituminous anthracite</td>
<td>thin</td>
<td>LW</td>
<td>1991</td>
<td>-</td>
<td>4</td>
<td>0.2–0.15</td>
<td>AGS</td>
<td>[23], [96]</td>
</tr>
<tr>
<td>Poland</td>
<td>9 (1.6%)</td>
<td>53% U</td>
<td>anthracite</td>
<td>thin slanted</td>
<td>LW</td>
<td>1985</td>
<td>0.3</td>
<td>1</td>
<td>4</td>
<td>over 50% 2-50%</td>
<td>PGS</td>
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<tr>
<td>Kazakhstan</td>
<td>10 (1.5%)</td>
<td>--</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2</td>
<td>--</td>
<td>10-70%</td>
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</table>

* Data obtained from [99]. ** The permissible exposure limit (PEL) is a legal limit in the United States for exposure of an employee to a chemical substance or physical agent such as Respirable Coal Mine Dust (RCMD).
5. Progress in RCMD Monitoring

In 1970, the coal mine operators and MSHA started using the “coal mine dust personal sampler unit” (CMDSU) to determine the concentration of respirable dust in the mine environment. This unit was being utilized to test the underground atmosphere by drawing mine air through a filter cassette that collects respirable dust. At the end of a full shift, the cassettes were collected and shipped to a specialized laboratory for analysis. The collected dust on each filter was then weighed under controlled conditions to determine the average concentration of respirable coal dust during the production shifts. An immediate problem with this method was that it takes several days (sometimes weeks) before the mine operators and MSHA to receive the results. Another critical problem with this method was that personal sampling for respirable coal mine dust could be only performed as an average concentration during a full shift. As a result, high transient/short-term concentrations of respirable coal dust events were not captured through the use of the 10-hour time-weighted-average (TWA) sampling method [4,23,59,108].

In the 1990s, NIOSH began conducting research and development to produce a new type of personal dust monitoring unit that could provide readings of dust levels in a near-continuous manner. This new device known as the “continuous personal dust monitor” (CPDM) allows the mine operators to promptly identify and respond to dust concentrations exceeding MSHA requirements. Through near real-time readings, the instrument allows the mine operators to determine dust concentrations, trigger dust control systems, and evaluate the effectiveness of the dust control methods [59,108].

Presently, the PDM3700 instrument manufactured by Thermo-Fisher Scientific is used to measure dust concentrations in the production workings in near real-time. During various MSHA–Industry dust partnership meetings and through NIOSH visits to mine sites, mine operators and mine workers have indicated that a second generation CPDM would need to be designed and manufactured to reduce its size, weight, and operating noise. The construction and operating features of this unit are still “mass-based” and “filter-based,” which means that the instrument uses a particulate filter mounted on an oscillating microbalance to measure dust concentrations. As a result, this instrument can only measure the combined mass of respirable coal dust, plus any respirable mineral dust and organic matter that is present in the mine air. The total mass of the RCMD collected by a respirable personal sampler is assumed to all become the miner’s RCMD dose. Nonetheless, the mass concentration does not necessarily represent the true RCMD dose received by the coal miner, especially for RCMD less than 4 μm. Not all of the RCMD inhaled into the miner’s respiratory tract will deposit in the lung to become the RCMD dose. A portion of the inhaled RCMD could be exhaled out of the respiratory tract during exhalation without deposition. This phenomenon is especially significant for submicron RCMD [7,108]. It is also critical to identify different constituents of RCMD in order to have a comprehensive understanding of the health effects. For a thorough chemical analysis, several filter media are needed to collect integrated samples during working shifts. For example, Polycarbonate-membrane (PC) filter is used for morphological and elemental analysis by scanning electron microscopy (SEM). Quartz fiber filter is used for organic analysis of RCMD, or Teflon filter is used for mineralogic analysis by x-ray diffraction (XRD) [112]. The efficiency captured by collector should be maximum for those filters since the total mass of the RCMD collected on a filter is assumed to all become the miner’s exposure dose. The summery of instrument development is presented in Table 3.

<table>
<thead>
<tr>
<th>Device Name</th>
<th>Country/Association</th>
<th>Description of the Sampling Operation</th>
<th>Sampling Positioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midget Impinger (1937)</td>
<td>U.S. Bureau of Mines</td>
<td>A hand-wrapped pump pulled the air into the impinger. Inside the device, the air emerged from a small orifice at high</td>
<td>Area sampling</td>
</tr>
<tr>
<td>Device Type</td>
<td>Description</td>
<td>Location</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Gravimetric Sampler (1964)</td>
<td>This device first removed particles beyond the respirable sizes, and small particles under 7 μm in size were collected on an elutriator. The elutriator is required to be held in a steady horizontal position to work correctly.</td>
<td>United Kingdom (MRE)</td>
<td></td>
</tr>
<tr>
<td>Personal Sampler (1969)</td>
<td>Particles over 7 μm removed by 10-mm nylon cyclone. The cyclone is attached to a filter that collects respirable dust up to a few ounces.</td>
<td>U.S. Atomic Energy Commission</td>
<td></td>
</tr>
<tr>
<td>CMDPSU (1970)</td>
<td>The air is drawn through a filter cassette that collects RCMD particles. Then at the end of each shift, filter cassettes are analyzed to measure the weight of dust. Polyvinyl chloride (PVC) filter with pore sizes less than 5 μm is usually used in this method. The total measurement of RCMD weight is averaged as an average concentration of RCMD for the shift.</td>
<td>U.S. Department of Labor, MSHA</td>
<td></td>
</tr>
<tr>
<td>Tyndallometer and SIMSLIN * (1981)</td>
<td>The principles employed in Tyndallometer included light scattering, real-time aerosol monitor. The principles employed in SIMSLIN is beta-ray attenuation and the change in the resonant frequency of a piezoelectric crystal.</td>
<td>U.S. Department of Labor, MSHA</td>
<td></td>
</tr>
<tr>
<td>CPDM (1991)</td>
<td>NIOSH began conducting research and development to produce a new type of personal dust monitoring unit using a Tapered Element Oscillating Microbalance (TEOM-based) personal dust monitor to provide readings of dust levels in a near-continuous manner by the PDM3700 instrument.</td>
<td>NIOSH</td>
<td></td>
</tr>
<tr>
<td>PDM3700 (2016)</td>
<td>This device is designed explicitly for MSHA’s rule for underground coal mine applications. PDM provides three primary current mass concentration, primary cumulative mass concentration, and percent of the limit.</td>
<td>Thermo-Fisher Scientific</td>
<td></td>
</tr>
</tbody>
</table>

* Safety in Mines Scattered Light Instrument.

6. RCMD Characteristics and Characterization Techniques

To properly understand the characterization of RCMD, a more detailed depiction of the respirable dust is required. Even now, no fundamental approach to systematically and provisionally classify coal mine dust has been proposed [17,21–23,109,113–115]. Nevertheless, various methods have been used to characterize RCMD, including scanning electron microscopy-energy-dispersive x-ray spectroscopy (SEM-EDX or SEM-EDS), thermogravimetric analysis (TGA), XRD, inductively coupled plasma-mass spectrometry (ICP-MS), Fourier Transform Infra-Red (FTIR) spectroscopy, atomic absorption spectrometry, and x-ray photoelectron spectroscopy (XPS) [5,7,9,17,21,109,116–121]. A standard methodology using SEM-EDX was proposed by Sellaro et al. [21] to characterize RCMD particles. Despite being widely used in various metallurgical applications and industrial mineral processing, the SEM-EDX technique was not applied for RCMD characterization before Sellaro et al. [21]. This approach is being progressively used to precisely explain the structure and composition of airborne particles that pose health hazards in industrial and environmental settings. For example, methodologies have been recently developed to study nano-size particles in the field of active welding [89,122]. To accurately describe a particle, different characteristics, including particle size, length, and shape are measured by SEM-EDX. Therefore, this characterization technique can provide a comprehensive array of data in a thorough analysis of RCMD.

The thermogravimetry analysis (TGA) is used to measure the changes in the weight of a dust sample when exposed to temperature [116]. The weight change typically plots
as the function of temperature in a thermogram. The data is used to explain chemical changes in the sample when heated [5, 116]. For many years, this technique has been used to determine the non-combustible mineral fraction of coal [22, 23, 123, 124]. TGA is a convenient and inexpensive method for obtaining additional knowledge about dust samples. Particularly, the mass percentages of coal and non-coal can be measured by TGA, and the carbonate and non-carbonate mineral fractions can also be estimated [125]. The data obtained by TGA may help researchers better understand how mining activities affect dust composition as well as provide insights into miner health outcomes in terms of dust characteristics. The TGA data for respirable dust samples taken from seven Appalachian mines showed that the carbonate and non-carbonate mass fractions can be very high in the non-coal fraction, while the coal to total mineral mass ratio is very low [125].

A summary of RCMD characterization studies from 1972 to the present is provided in Table 4. According to the National Academies of Sciences, Engineering, and Medicine (NAS) [23], the early investigation on dust particle size was presented in 1959 at the Johannesburg conference, in which initial efforts were to measure the size of RCMD particles accumulated in the lungs based on mineral autopsy results. Based on the analyzed pathological samples from the lungs of a former coal miner, dust particles with a diameter less than 5 μm were determined to enter the air exchange region [3, 21]. However, a drawback of the analysis was that only a series of particle size deposition values of approximately 3 to 10 μm were covered by the available data [5, 10]. Many researchers have suggested that further investigations should address the physical and chemical properties of RCMD and its dependency on the geographic regions [28, 97, 119]. Morgan et al. [30] suggested that the variations in CWP prevalence cannot be fully explained only by exposure duration, and all contributing factors should be taken into account. For example, the physical and chemical compositions of coal may be responsible for geographical variations in prevalence [30]. A few studies have been conducted to investigate the total RCMD composition and its relationship with the exposure health risks [7, 15, 20, 22, 41, 126]. The relationship between the CWP prevalence and bioavailable content of coal dust studied by Huang et al. [41] showed a correlation with bioavailable iron and pyritic sulfur, but not with coal rank and silica. Furthermore, a review of several reports revealed that rapid pneumoconiosis cases are likely to be misdiagnosed with silicosis as CWP [36]. Several reasons including high silica content of mines in the southern Appalachian region, thin coal seams containing a high percentage of quartz, small sizes of mines, and an increase in the mines’ shift hours resulting in coal and silica dust accumulation support this claim [7, 38].

In the United States, the investigation of RCMD content in the Appalachia region has revealed more details about probable sources of RCMD. A higher concentration of aluminosilicate in Appalachian mines is primarily attributed to rock dusting application and cutting or drilling of rock strata [7, 22]. Furthermore, particle size analysis based on sampling location showed that samples collected from active cutting or drilling operations and in the return airways have elongated and smaller-sized dust particles than in the intake airways [7, 8, 19, 22, 79]. Analysis of the overburden roof and the underlying floor strata of Appalachian basin rock indicated that northern Appalachian mines have a higher percentage of carbonate particles than central and southern Appalachian mines due to higher rock dusting of mines producing from relatively thicker coal seams [7, 15, 20, 22, 122, 127].

The traditional method of RCMD monitoring based on current regulation relies on the concentration of silica and total mass fraction [23, 119, 125]. The recent resurgence in rapidly progressing CWP may be localized in the central Appalachian area [23]. Several investigators have proposed a number of potential reasons for the continued prevalence of pneumoconiosis of coal workers, including longer shift times, changes in mining technology, increased mining of higher quartz-bearing coal, and extraction of roof and floor rock strata for mining thin coal seams [11, 39, 40, 79]. The content and characteristics of RCMD particles based on the geographical location of a coal mine requires further studies.
The issue of particle size versus particle mass and total mass or silica content is still in debate [7,23]. Due to the detection limits of instruments, it has been challenging to characterize very fine dust particles in a sample [7,17]. Therefore, there seems to be not enough information about the relative occurrence or impact of submicron (100–1000 nm) particles and their correlation with the exposure health impacts [7,129]. A comprehensive study for both submicron and supra-micron RCMD particles was conducted by Sarver et al. [7] in which the size distribution of RCMD for 76 samples from US coal mines were analyzed. The result showed that RCMD samples are largely submicron rather than supra-micron particles, despite probably ignoring the finest particles. In their experiment, more than 50% of particles accounts for very fine particles (including DPM) and over 75% of total particulates are in the range of submicron. Among different sources of RCMD (i.e., rock strata, rock dusting), diesel particulate is most likely in submicron size, while other sources can be observed in both submicron and supra-micron size ranges [7].
<table>
<thead>
<tr>
<th>Study</th>
<th>Sampling Locations (Sites)</th>
<th>No. of Samples</th>
<th>Instrument</th>
<th>Characteristic Technique</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn et al. (1972 &amp; 1973)</td>
<td>Western Pennsylvania (Mathies and Robena mines)</td>
<td>6</td>
<td>Horizontal Elutriator</td>
<td>• BAHCO centrifugal classifier&lt;br&gt;• Micropycnometric method&lt;br&gt;• Atomic absorption spectrometry&lt;br&gt;• Optical microscopy</td>
<td>As anticipated, there is little density variation between particle size fractions, but significant increases occurred in total surface area and projected area as particle size decreased&lt;br&gt;Free silica content increases with decreasing particle size fraction within the respirable size range&lt;br&gt;In the trace metal category, aluminum, zinc, and iron content increase with decreasing particle size but calcium decreases</td>
</tr>
<tr>
<td>Morgan et al. (1973) [30]</td>
<td>Pennsylvania (8 mines), West Virginia (9 mines), Kentucky (3 mines), Virginia (2 mines), Alabama (2 mines), Illinois (2 mines), Utah (2 mines), Ohio (1 mine), Indiana (1 mine), Colorado (1 mine)</td>
<td>9076 miners</td>
<td>A large field study to determine the prevalence of CWP and Fibrosis</td>
<td>• Radiographic</td>
<td>Physical and chemical composition of the coal dust are factors that could be responsible for the prevalence of lung diseases in different geographic regions&lt;br&gt;Coal rank is another factor that could play a significant role in the prevalence of lung diseases</td>
</tr>
<tr>
<td>Stein and Corn (1975) [130]</td>
<td>Pennsylvania (Pittsburgh, Lower Freeport, and Lower Kittanning)</td>
<td>8</td>
<td>Millipore GS membrane filter</td>
<td>• Bahco centrifugal particle classifier&lt;br&gt;• Optical microscopy&lt;br&gt;• Orr surface area-pore volume analyzer (2100A)</td>
<td>The Bahco classification is a helpful instrument for coal dust characterization to classify different particle sizes&lt;br&gt;It should be possible to understand those CWP-related dust properties through characterizing respirable coal dust of various mines as well as by analyzing the chemical composition of the same size fractions&lt;br&gt;In addition to weight concentration, there are other vital factors for coal dust characterization such as particle size, shape, density, specific surface area, and chemical composition</td>
</tr>
<tr>
<td>Kriegseis and Scharmann, (1985) [131]</td>
<td>Germany (Ruhr coal field)</td>
<td>1</td>
<td>Bergbau-Forschung GmbH, Essen, with BAT II</td>
<td>• Thermoluminescence method</td>
<td>The quartz surfaces are further polluted by dust samples from lower-rank coal seams.</td>
</tr>
<tr>
<td>Year</td>
<td>Location(s)</td>
<td>Study Details</td>
<td>Techniques</td>
<td>Notes</td>
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</tr>
<tr>
<td>1986</td>
<td>Pennsylvania (4 mines), West Virginia (1 mine), Ohio (4 mines)</td>
<td>Lee (1986) [132]</td>
<td>Infrared spectroscopy, Emission spectroscopy, Atomic absorption</td>
<td>A possibly useful parameter for connection with the particular toxicity of coal mine dust could be the amount of unprotected free-quartz surfaces rather than the quartz content.</td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>Appalachian bituminous coalfield (Upper Freeport, Pittsburgh, Kittanning, Coalburg, and Pocahontas)</td>
<td>Kim (1989) [113]</td>
<td>Cascade impactors, X-ray powder diffraction photographic technique</td>
<td>The chemical composition of coal dust is substantially dependent on its size and location. Different locations have shown the particle size of coal dust samples that can be important in underground coal mines dust controlling. The dust in intake air and exhaust from shuttle cars are significant sources of respirable coal dust in underground areas.</td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>US (1 mine)</td>
<td>Grayson and Peng (1989) [119]</td>
<td>Cascade impactors, Dorr-Oliver 10-mm cyclones and DuPont P2500, Infrared Spectrometry</td>
<td>Coal seams and location of sampling have an important role in the coal dust characterization. Illite, calcite, kaolinite, quartz, dolomite, siderite, gypsum, anhydrite, and pyrite are nine typical minerals found in the coal seams.</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>Illinois (1 coal mine), Pennsylvania (6 coal mines and 1 clay mine), West Virginia (1 powdered tunnel quartz rock)</td>
<td>Wallace et al. (1994) [120]</td>
<td>Dorr-Oliver 10-mm cyclones and DuPont P2500, SEM-EDS</td>
<td>There was considerable variation among the control and sample means for an Illinois bituminous coal mine dust, two western and one central Pennsylvania bituminous coal mine dust low-temperature ashes, and a clay mine and mill dust sample, but not for an anthracite coal mine dust and two central Pennsylvania bituminous coal mine dust low-temperature ashes.</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>Pennsylvania (7 mines), Illinois (2 mines), Colorado (1 mine)</td>
<td>Harrison et al. (1997) [121]</td>
<td>Cyclone, filter, and impactor, SEM-EDS</td>
<td>Coal workers of high coal rank mines can be at a higher level of lung disease risk.</td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Location</td>
<td>Sample Size</td>
<td>Methods</td>
<td>Observations</td>
<td></td>
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<td>-------------------------------</td>
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<td>-------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>Sapko et al. (2007) [114]</td>
<td>MSHA’s Districts bituminous districts</td>
<td>163 *</td>
<td>Sieve, Acid leaching, Sonic sieving, Low-temperature ashing</td>
<td>One or more factors like the biologic availability of quartz particle surfaces have been observed for anthracitic coal areas in the US National Study of Coal Workers’ Pneumoconiosis (NSCWP) as the higher prevalence of diseases per unit cumulative exposure</td>
<td></td>
</tr>
<tr>
<td>Jing et al. (2010) [9]</td>
<td>China (Jining and Shandong)</td>
<td>4</td>
<td>Laser particle size instrument (Beckman Coulter LS 13320, the United States), FTIR spectroscopy, XPS spectroscopy</td>
<td>Dust particle size in intake airways is finer than those measured in the 1920s. The significance of these finer coal dust sizes is relevant to the amount of rock dust required to prevent coal dust explosions.</td>
<td></td>
</tr>
<tr>
<td>Sellaro et al. (2015) [21]</td>
<td>Central Appalachia (1 mine)</td>
<td>3</td>
<td>MSA Escort ELF pump with a Dorr-Oliver cyclone, SEM-EDX</td>
<td>The surface of coal dust and pore volumes increases with a decline in the size of particles. Moreover, unlike the average pore size, the surface roughness increases. Analysis of the XPS spectrum indicates that carbon on the surface of coal dust increases steadily with a decrease in the size of coal dust, and oxygen decreases gradually. Respirable coal dust has lower wettability and higher hydrophobicity in comparison with large coal particles.</td>
<td></td>
</tr>
<tr>
<td>Johann-Essex et al. (2017) [22]</td>
<td>Central Appalachia (6 mines)</td>
<td>210</td>
<td>ELF sampling pumps and cyclones, CCSEM-EDX XRD</td>
<td>SEM-EDX is a valid technique to be used for characterization of coal mine dust. Shape, dimensions, and particle composition are determined by SEM-EDX and other parameters like volume and mass particles obtained as a result of the analysis. Particle angularity is another important controlling factor of tissues and respirable dust interaction. Unlike the belt-drive sample, distribution of particle composition by mass in roof bolt and intake samples significantly increased when the number of particles analyzed (n) increased. Distribution of particle composition by number showed that there was a similar result across all n values for samples from belt-drive, roof bolt, and intake air when the number of particles analyzed on RCMD increased. Established a CCSEM-EDX ** routine to provide a greater data acquisition rate and a consistent analysis of RCMD characterization.</td>
<td></td>
</tr>
</tbody>
</table>
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Northern Appalachia (2 mines)
- TGA

- Collected samples near the face in both continuous miner and longwall indicated high quartz and alumino-silicate, unlike carbonaceous particles, for which the source is believed to be rock dusting
- Samples from northern Appalachia had higher carbonaceous distribution than central Appalachia
- The size of RCMD particles was significantly smaller in mid-central Appalachia than those from central and northern Appalachia

Central Appalachia (6 mines)
Northern Appalachia (2 mines)
76 (sample sets)
- Escort ELF air sampling pumps with 10-mm nylon Dorr-Oliver cyclones
- SEM-EDX
- ICP-MS
- 1-NP and PAH analysis

- Four major sources of RCMD were found to be coal seam, rock strata, rock dusting, and diesel engine emission
- The distribution of alumino-silicate and silica in all mines was almost similar
- Coarser carbonaceous particles indicated more of the carbonaceous particles in this mine are probably coal dust particles, while the finest carbonaceous particles are more likely associated with diesel exhaust
- Other notable differences in particle size distributions between sampling locations showed the occurrence of coarser carbonaceous and carbonate particles in the return airway and feeder locations versus other locations

Central Appalachia (15 mines)
Northern Appalachia (5 mines)
Mid-west/Illinois basin (2 mines)
Western basin (2 mines)
166
- Oliver cyclones
- SEM-EDS

- There was a difference in the mineralogy of samples based on geographical location and region
- The concentrations of alumino-silicate and silica were higher in central Appalachia than northern Appalachia and the western basin
- Characterization of coal dust samples changes remarkably by geographical locations

* The dust samples collected by mine inspectors for compliance with 30 CFR 75.403. ** The dust samples collected by mine inspectors for compliance with 30 CFR 75.403.
7. Discussion

The analysis for probable reasons for the substantial increase in the CWP incidence rate is rather complicated. Changes in mining practices, technology advancement, thin coal seam mining, rock dusting, and new cutting machinery may each contribute to the occurrence of new CWP cases in the United States [4,5,10,23,133,134]. Further investigations are required to identify the root causes of the resurgence of the lung diseases and the contributing factors [7,10,23]. The majority of disease incidences are reported to be in underground coal miners. Therefore, the vast majority of research studies focus on RCMD monitoring and control in underground mines. However, it is worth mentioning that respiratory lung disease is also a prevalent health issue among surface coal miners.

Generally, the total mass concentration of RCMD and fraction of silica mass are two metrics that are currently used for RCMD monitoring and control [7,23,135]. In the United States, CPDM indicates significant technological progress, as it presents near real-time observations of ambient RCMD concentrations while carrying out operations. In cases that RCMD content in the air exceeds the permitted level, the CPDM alerts miner executives to act immediately, either by changing workers’ location or by implementing mining practices in order to mitigate RCMD content (MSHA, PH89-V-1 (27)) [23,133]. However, the efficacy of the current monitoring approach based on the measurement of RCMD total “mass-concentration” is still unclear. Many have questioned whether reducing the exposure limits will actually target the root cause of the problem. Although the connections between coal miners RCMD exposure and respiratory diseases have been studied for decades, the contributing factors that cause the progression of the disease are not yet identified [7,12,21–23,125,129,136].

Several researchers aimed to investigate the health effect of quartz as a major inorganic part of RCMD [115,121]. However, other studies indicated that neither CWP nor PMF could be credited for quartz unless the concentration of quartz reaches 10% [137–140]. The coal rank is another contributing factor that may play a role in the progression of CWP [33,141]. Several studies confirmed that there is a higher risk of CWP for higher coal rank, even at the same level of RCMD concentrations [38,142]. Gamble et al. [38] proposed higher rank coal as a plausible factor for CWP prevalence within the Appalachian region. In many bituminous coal mines, the higher prevalence of CWP has also been linked to a higher quartz content in respirable dust [143]. Previous studies indicated that an apparent link between the coal rank and CWP may be attributed to the particle surface charge and mineralogical composition of RCMD [127]. However, the causal effects of coal rank have not been exclusively investigated [108]. Moreover, there are research studies suggesting that unlike bioavailable iron and pyritic sulfur, there is no correlation between coal rank and CWP [41,115]. Beer et al. [12] conducted the first systematic review of the coal dust exposure to investigate whether the prevalence of ILD is pure coal or coal mixed with silica minerals. In this review, the author found that the level of evidence is limited for causal links between exposure to pure coal powder and ILD. In order to support the hypothesis, however, further analysis of the data related to miners exposed to none or very small content of mineral particles is required.

It is clear that more research on physical and chemical properties of RCMD is needed to understand the root causes of CWP incidences and its recent resurgence. Characteristics parameters such as particle size distribution (particularly in the smaller fractions enriched with minerals), mineral composition, trace element presence, and particle shape and angularity are all important parameters that need to be examined closely.
The machinery specifications and mineralogical composition of the coal and surrounding rock strata should be considered as contributing factors to the total dust concentration and characteristics of the RCMD [9,115,118,121]. Depending on the coal mining operations and the mining equipment, generated RCMD can be coarse or fine in size. Both coarse and fine coal mine dust can inevitably be inhaled by coal miners while performing their work. Various studies suggest that RCMD concentration varies depending on the locations within underground mines. Miners working between the shearer and the air outlet from the longwall, at the junction of the longwall with the tailgate, loading-shearer, and drilling operators are at the highest risk of occupational lung diseases [7,8,143].

To date, there has been no comprehensive study to investigate the relationship between RCMD characterization and respiratory deposition. Characterization results should be used as guidance for prospective lung deposition and toxicity research that takes into account the differences of RCMD source, particle size distribution, and mineralogical groups to which miners are exposed to cumulative RCMD [141]. Many studies demonstrate that by increasing the tidal volume (whether by increment activity or through the ventilation system), a more considerable amount of dust particles will be deposited in the human respiratory system. Furthermore, size fraction of particle deposition may differ by the breathing scenario, pause fraction, and breathing frequency for adults and young workers. It is crucial to identify different constituents of RCMD in order to have a better understanding of the health effects. Not all of the RCMD particles inhaled into a miner’s respiratory tract will be deposited in the lung. A portion of the inhaled RCMD will be exhaled out of the respiratory tract during exhalation. Therefore, the total amount of RCMD inhaled may not be the representative of the actual RCMD exposure dose. This phenomenon is especially significant for submicron particles [122,144]. Currently, the mine health related RCMD personal sampling is based on the mass concentration, which may not correctly represent the true RCMD dose received by coal miners, especially for particles less than 4 μm in size [23]. Therefore, the correctness of using mass-concentration-based RCMD sampling as an index to protect miner’s RCMD exposure is questionable. The number-concentration-based RCMD samples could be an alternative and ideal index for RCMD dose estimations. There are a variety of parameters that affect RCMD characterization (i.e., mineralogy properties, particle size, shape) in mines. For instance, recent findings by Sarver et al. [128] supported the hypothesis that RCMD characterizations among mining regions differ substantially. Mineralogy composition and distributions of the RCMD particle size, which is impacted by geographic location, are essential to understanding the recent CWP resurgence [128].

Overall, the effectiveness of MSHA’s new dust rule (i.e., decreasing the PELs and use of CPDM) will possibly take years to be properly assessed [29]. Nonetheless, the current regulation requires sampling of RCMD mass concentration using CPDM devices (79 Fed. Reg. 84, May 1, 2014) [145]. The gravimetric method is also used to validate CPDM measurements. There are, however, many factors that contribute to the development of lung diseases, including, but not limited to, submicron-size fractions, particle number, DPM, and elemental content. Although time and costs for the characterization of RCMD are likely to be prohibitive for regular monitoring, they offer valuable information to better understand the composition of RCMD and its relationship with the development of lung diseases among coal miners.
8. Conclusions

In the United States, the increase in the rate of CWP in the mid-1990s has renewed the urge among medical and science researchers to investigate the primary root causes of the problem. This paper provided a review of RCMD research studies focusing on characterization, respiratory deposition, and exposure health effects. There have been tremendous efforts to identify the contributing factors in developing lung diseases among coal miners. The analysis of possible explanations for this dramatic increase seems very complicated. Technological development, level of automation, thin coal seam mining, application of rock dusting, and changes in mining practices can all contribute to the increase of lung diseases. No particular medical therapy is useful in controlling and removing the effect of coal mine dust lung diseases such as CWP. Hence, attempts to reduce RCMD exposure along with medical monitoring for early disease diagnosis and elimination from exposure is crucial to protect the health of a miner.

Current MSHA regulation requires the use of a CPDM for the measurement of RCMD mass concentrations in near real-time and determining compliance with the regulatory exposure limit. However, the precision of using mass-concentration-based RCMD sampling as an index to protect miner’s RCMD exposure is questionable. The accuracy of particle number-concentration-based RCMD monitoring systems should be assessed, and their effectiveness should be compared with the mass-based monitoring method. Furthermore, it is crucial to investigate the relationship between the characterization and lung deposition of RCMD in order to understand the true exposure dosage. The distribution of CWPs varies in different US coal regions. Several studies indicated that small mines located in Central Appalachia are at a high risk of CWP prevalence. Therefore, future research studies should focus on identifying the key difference in characteristics of coal dust between underground mines in coal regions in the western and eastern United States.


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Conflicts of Interest: The authors declare no conflicts of interest.

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