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Original Research

Particulate matter emissions from open pit mines; measurement methodologies, instruments, and research undertaken

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A B S T R A C T

Particulate matter is one of the primary pollutants in open pit mining operations. Measurements must be taken to control particulate matter created during open pit mining activities and to compare them to the regulatory limits. Numerous studies have been undertaken to estimate particulate matter emissions produced by open pit mining. It was discovered that the research were largely conducted on coal mines (69.4%), with little study done in other mining types. Research studies on particulate matter estimation took into consideration mostly machine characteristics (loader bucket volume, truck capacity, number of truck wheels etc.) and atmospheric conditions (air temperature, wind speed, relative humidity etc.). This study emphasizes on particulate matter measurement methods along with other measuring parameters and equipment for particulate matter estimation (TSP, PM_{10}, PM_{4}, $PM_{2.5}$, and PM_{1}).

Keywords: Open pit mine, PM_{1}, $PM_{2.5}$, PM_{10}, TSP.

Introduction

Air pollution is a major health risk. Particulate matter (PM) is one element that contributes to air pollution (Choudhary and Garg 2013; Kim et al., 2015; Beloconi et al., 2018; THHP, 2019). There is a great deal of risk to people, other living things, and the environment because of the failure to manage air pollution. The mining industry is one of the pollutants that contributes to air pollution (Hendryx et al., 2020). Large amounts of dust released during both underground and surface mining activities exacerbate environmental problems (Kahraman and Erkayaoğlu, 2021). Dust and PM, which accumulate above the limit values in various places in and around mining areas, negatively affect the health of those working in mines and those living around them and can also cause serious damage to plants and other living things in the vicinity. For this reason, it is extremely important to measure and control dust and especially PMs that cause air pollution, especially in the mining industry. In this study, PM measurement methods are mentioned and at the same time, studies on PM measurement during open pit mining operations are compiled. The parameters used in these studies are examined. This compilation study also provides a perspective on which parameters are used in PM modeling in the open-pit mining industry.

1. Particulate matter concentration measurement methods

There are two ways in which PM concentration measuring devices operate. Under the first method, air quality measurement stations continuously record PM concentrations at predetermined intervals (e.g., seconds, minutes) and instantly monitor particulate matter content. These highly sensitive measurement devices can be controlled remotely via telemetry, or wireless transmission, and they can run for weeks or months once started with little or no operator involvement. However, high standards for calibration, quality control, and maintenance are necessary for accurate measurement. In addition to air quality monitoring stations, handheld or portable PM measuring devices with inexpensive optical sensors can also be used to record at specific intervals. However, devices operating on this principle are generally used to monitor dust exposures in workplaces due to their low sensitivity (NZG, 2009).

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In the second method, PM concentrations are collected in filters and analyzed in laboratories at the end of the measurement period. Due to the laborious method of measuring PM concentration in ambient air and the complex nature of particulate matter, the chosen method can significantly affect the measurement result. Therefore, the choice of method is extremely important for accurate measurement of PM concentration. US Environmental Protection Agency (USEPA) particle monitoring methodologies are classified as reference or equivalent methods. Reference methods are referred to as gravimetric (such as measuring directly by mass), while equivalent methods are referred to as methods based on reference methods (NZG, 2009). Leading PM concentration measurement methods are given in Figure 1. The unit of measurement for PM concentrations is generally mg/m^3 or µm/m^3.

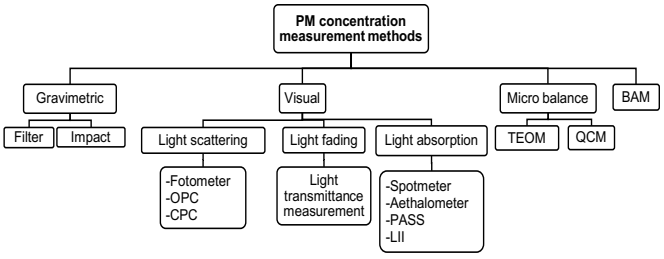

*Figure 1. PM concentration measurement methods (*modified from Amaral et al., 2015*)*

1.1. Gravimetric method

Gravimetric sampling and analysis methods are commonly used to quantify the amount of airborne particulate matter collected from workplace environments (O'Connor et al., 2014; Walley and Zandi, 2016). These measurements are frequently performed to estimate occupational exposure to airborne particles and/or to assess the efficacy of air pollution control technologies. Furthermore, gravimetric analysis of airborne particles is frequently supplemented by other analytical methods used to determine the concentrations of specific chemical agents in occupational environments (O'Connor et al., 2014). This method's main goal is to collect particulate matter in a filter. Air is drawn from a sampler at a certain flow rate with the help of a pump and collected in a pre-weighed filter. Then, the mass of PM is determined with the help of filters weighed under laboratory conditions, and the suspended PM concentration is determined by dividing the PM mass by the volume of air drawn through the filter by the pump. There are various types and manufacturers of samplers working on the gravimetric principle, from individual dosimeters to fully automatic units (Pfeiffer, 2005). With this principle, the average mass concentration for the sampling period is obtained. However, when measuring with this method, the flow rate of the device to be used and the laboratory conditions for weighing are extremely important. In addition, time-dependent concentration values are produced with the gravimetric method, and it is not possible to measure continuous values (minutes, hours, etc.) (Winkel et al., 2014; Walley and Zandi, 2016). With the gravimetric method, PM_{10} and $PM_{2.5}$ concentrations (Pfeiffer, 2005; Mojala et al., 2017) and TSP concentration are found using the equations 1-3 (Mojala et al., 2017). Here, the volume of air sampled for $PM_{2.5}$ (V) is calculated by the sampler's microprocessor, rather than manually as in high-volume PM_{10} analysis (Pfeiffer, 2005; EPA, 2008).

$$TSP = \left[\left(W_f - W_i\right) - \left(CW_f - CW_i\right)\right]/V \quad (1)$$

$$PM_{2.5\ \&\ 10} = \left(W_f - W_i\right) \cdot 10^3/V \quad (2)$$

$$V = Q_a \cdot t \quad (3)$$

where:

W_f : Mass of filter after sampling (mg)
W_i : Mass of the filter before sampling (mg)
CW_f : Mass of the powder cone after measurement (mg)
CW_i : Mass of the powder cone before measurement (mg)
V : Sampled air volume (m^3)
Q_a : Average air flow rate during the sampling period (m^3/min)
t : Sampling time (min)

i. Filter-based samplers are widely used because their cost is low, atmospheric particles can be easily stored, and the collected PM can be used later in simple and/or complex analyses (EPA, 2008). In this method, particles are collected in a pre-weighed filter. Filters are weighed before and after sampling ("loaded" and "unloaded" filters) under standard temperature and relative humidity conditions. The difference between both readings is equal to the mass of the PM (Baumann et al., 2006; Giechaskiel et al., 2014; Amaral et al., 2015; Walley and Zandi, 2016). Since filters are sensitive to environmental factors such as relative humidity, their selection is extremely important. Traditional filters are made of glass fiber and their surface is protected from chemical reactions by a special coating (such as Polytetrafluoroethylene, PTFE). For this reason, PTFE-coated glass fiber filters are widely used by EPA and European Union institutions (EPA, 2008; Walley and Zandi, 2016). The USA also recommends the use of PTFE type filters with legal regulations (Giechaskiel et al., 2014). On the other hand, it has been stated that quartz fiber filters should be used for PM_{10} measurement according to the EN 12341, and glass fiber, quartz fiber, PTFE or PTFE-coated glass fiber filters should be used for $PM_{2.5}$ measurement according to the EN 14907. It has also been stated that EN 12341 needs to be revised to be consistent with EN 14907, and that any of the four filters listed in EN 14907 can be used in both PM_{10} and $PM_{2.5}$ reference samplers (Harrison et al., 2006).

ii. Impactors are devices used to measure the size distribution in the mass with the gravimetric method, and some types have multiple holes (Amaral et al., 2015). In this measurement method, aerosols pass through sequential filter stages. At each stage, an air jet containing aerosol reaches the impinging plate and particles larger than the filter diameter are collected for the stage. While the smaller particles follow the gas flow surrounding the collection plate and are collected in the next stage where the holes are smaller and with higher air velocity conditions, this process continues until the smaller particles are cleared in the final filter (Vincent, 2007). Low-pressure cascade impactors (Andersen impactor, Dekati Low Pressure Impactor (DLPI), Berner Low Pressure impactor (BLPI), etc.) used for measurements of PM size distributions are generally suitable for size ranges ranging from 30 nm to 10-20 µm. Sampling can be done in lower size ranges with filters. Due to the sampling method, the particles obtained can also be used for additional analyses (Nussbaumer et al., 2008).

1.2. Optical method

Optical particle monitors utilize the interaction between airborne particles and visible, infrared or laser light (Pilling et al., 2005) for measurement. Optical Particle Counters (OPC) work on the principle of light scattering to detect the size and number of individual particles. OPCs are used in aerosol research in long-

term monitoring networks. The size of particles detectable with OPCs is approximately 0.05 to 50 µm, with general measurement ranges from 0.2 to 30 µm. Although size measurements with OPCs are very precise, their accuracy depends on particle composition and shape (EPA, 2008). Real-time monitoring of PM_{10} concentrations can be achieved using optical instruments (Walley and Zandi, 2016). In the optical measurement method, aerosol particles are illuminated with a beam of light. With the particles spreading in all directions, a part of the light beam is transformed into other forms of energy (absorption). The extinction of light is calculated by scattering and absorption (Giechaskiel et al., 2014). Optical instruments used to measure particle concentration in real time are based on the principles of scattering, absorption and light extinction (Giechaskiel et al., 2014; Amaral et al., 2015; Walley and Zandi, 2016).

i. Light scattering devices absorb sample air from a laser-illuminated chamber. A photodetector, which indicates the degree of light beam scattering, is used to classify airborne particles (Giechaskiel et al., 2014; Winkel et al., 2014; Amaral et al., 2015). The photodetector's signal converts the categorized particles into mass concentration by employing a calibration constant that is predetermined at the factory with a particular calibration aerosol (Winkel et al., 2014). Light scattering devices are generally portable, have an internal pump, are equipped with batteries and data storage, and can provide continuous data (Pilling et al., 2005; NZG, 2009; Winkel et al., 2014). Some devices can simultaneously determine several mass fractions (such as PM_{10}, $PM_{2.5}$, PM_1) or count the number of particles in a series of size channels. The main disadvantages of this method are that the optics inside the device can be contaminated with PM and the concentration readings can differ from the actual values because the particle size, shape, density and refractive index of the measured PM differ from the aerosol used to calibrate the device (Winkel et al., 2014). Nephalometers and/or transmissometers are widely used in the USA to determine visibility loss due to airborne particulate material, especially in national park areas (Pilling et al., 2005). Devices operating on this principle are generally used to monitor dust exposures in workplaces. Over the last few years, some of these devices have been adapted for environmental monitoring with varying degrees of success. In addition, they are more suitable for use in research or in low-level survey studies due to their measurement sensitivity and not being suitable for continuous monitoring (NZG, 2009).

ii. Light fading: The light transmitted from the exhaust can be measured with opacity meters. In addition, it has been stated that measurements based on light extinction depend on the particle concentration, shape and composition, as well as the path length and wavelength of the light (Giechaskiel et al., 2014).

iii. Light absorption: Measuring devices based on the principle of light absorption measure the concentration of black carbon that forms the aerosol in motor vehicles. Black carbon is a positive radiative substance that strongly absorbs light and therefore contributes to climate change, and due to this feature, it has been extensively used in atmospheric measurement studies (Giechaskiel et al., 2014; Amaral et al., 2015). Common techniques used to measure aerosol absorbance include (i) the difference method, where the absorbance is derived from the difference between extinction and scattering, (ii) filter-based methods, which measure light attenuation by PM collected on a filter, (iii) Photoacoustic spectroscopy, which measures black carbon through heat particles and (iv) laser-induced incandescence (LII). The last two methods measure black carbon by heating particulate matter and the particles absorb light (Giechaskiel et al., 2014).

1.3. Microbalance principle

There are two main measuring devices in the microbalance method: conical element oscillating microbalance (TEOM) and quartz crystal microbalance (QCM) (Amaral et al., 2015). Particulate matter monitoring devices using TEOM technology are "gravimetric" devices that draw ambient air through a filter by continuously heating it (50 °C) at a constant flow rate, continuously weigh the filter, and calculate particle concentrations in near real time (EPA, 2008; Winkel et al., 2014). Although these devices are used in the United States by many government agencies to obtain $PM_{2.5}$ and PM_{10} mass concentration data, they are only approved as an equivalent method for PM_{10} sampling (EPA, 2008). The TEOM measurement technique is based on a replaceable filter cartridge placed at the end of a hollow conical tube. The wider end of the pipe is fixed, particles accumulate as the air passes through the filter, and since the flow rate is constant throughout the sampling, the mass concentration can also be calculated (Baumann et al., 2006). The filtered air then passes through the conical tube to a flow controller. The conical pipe with the filter at the end is kept oscillating in clamp-free mode (Figure 2).

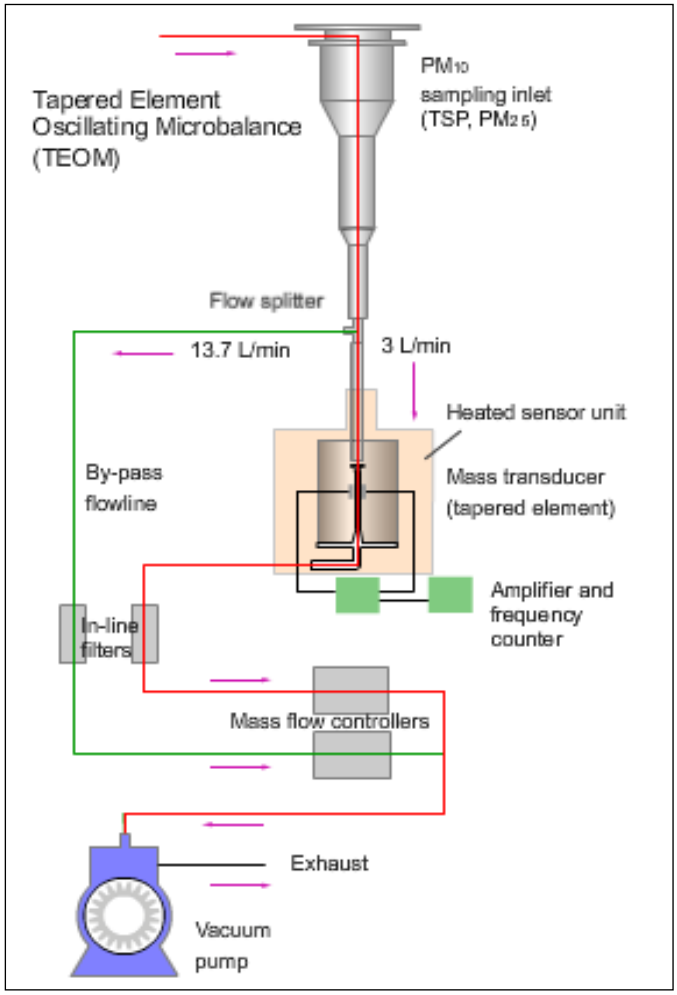

Figure 2. Working principle of conical element oscillating microbalance (TEOM) (Url-2, 2023)

The frequency of oscillation depends on the physical properties of the conical tube and the mass at its free end (Nosratabadi et al., 2019; Url-1, 2023). On the other hand, in this method, evaporation of PM material may occur due to sample flow heating, which may cause the actual PM concentration to be underestimated (Grim and Eatough, 2009; Winkel et al., 2014). PM concentration

changes collected in TEOM devices are affected by airflow, relative humidity, temperature, gaseous pollutants and particulate matter characteristics (Li et al., 2012). For this reason, it has been stated that the concentration value calculated during measurement with the TEOM device in England should be multiplied by a factor of 1.3 (Pilling et al., 2005; Harrison et al., 2006). TEOM monitors are currently used only for measuring PM_{10}, $PM_{2.5}$ or PM_{1} concentrations. However, airborne particle concentrations are normally low and therefore long sampling times or the use of high volume pumps are necessary to collect sufficient particles to perform an accurate gravimetric analysis and/or more specific chemical or biological analysis of the collected material (Nosratabadi et al., 2019) . Devices with TEOM analyzers are widely used both in the UK and the rest of the world (Pilling et al., 2005; Walley and Zandi, 2016). Quartz crystal microbalance (QCM) devices have piezoelectric properties that change the resonance frequency when a small mass is added to the quartz crystal surface. In these devices, particles are deposited by electrostatic precipitation in a thin quartz crystal resonator (EPA, 2008; Giechaskiel et al., 2014). On the other hand, QCM-based devices use the detection electrode of the quartz crystal as a collision plate. Particles in the air are sampled into the detection chamber and then deposited onto the crystal electrode via inertial force. However, it has been stated that these devices have significant disadvantages such as splashing of particulate matter due to poor adhesion, the need for frequent cleaning of the crystal electrode, and uneven distribution of collected particles (Ngo et al., 2019). Nevertheless, these devices can measure the mass concentration of 100 µg/m^3 aerosol in less than a minute (EPA, 2008).

1.4. Beta ray attenuation principle (BAM)

Beta-ray attenuation particle analyzers are the most widely used method for measuring ambient PM_{10} concentrations in national networks across Europe (Pilling et al., 2005). In addition, in Türkiye, measurements are made with devices working with this method at air quality stations in some provinces affiliated with the Ministry of Environment and Urbanization. The devices automatically measure and record airborne particulate matter concentrations (mg/m^3 or µg/m^3). Devices working with this principle collect the particulate matter in the air on the strip filter with the help of a pump. With the beta ray source coming from a radioactive source (Carbon-14 or Krypton 85), fixed high-energy electrons are emitted from the clean filter band to the particulate matter collected on the filter along a point, and these beta rays are detected and counted by a sensitive detector. The system automatically advances this band point to the sample spray system, where the vacuum pump then draws a measured and controlled amount of dust-laden air through the filter band and fills it with ambient dust. At the end of the sample hour, this dirty spot is placed back between the beta source (Carbon-14 or Krypton 85) and the detector, causing attenuation of the beta beam signal used to determine the mass and volumetric concentration of particulate matter on the filter band (Figure 3). This mass is used to calculate the volumetric concentration of particulate matter in the ambient air (Pilling et al., 2005; Baumann et al., 2006; EPA, 2008; Kamyotra, 2012; Url-3, 2023). Samplers working with the BAM principle are the only systems that continuously measure the mass concentration of particles by extraction and are not affected by chemical composition, size or color changes in the particles (Castellani et al., 2014). Although the filter material in the monitors of devices operating on this principle is generally not heated, in some analyzer configurations the inlet system can be heated to reduce the relative humidity in the sample, minimizing the water content of the particulate matter mass (Pilling et al., 2005; Winkel et al., 2014). Glass fiber filters are commonly used in particle analyzers that work on the beta attenuation principle. Additionally, while these monitors can produce half-hour average mass concentrations, a 24-hour averaging period is required for typical ambient concentrations to obtain sufficient particle accumulation for accurate estimation (EPA, 2008).

Comparison of PM_{10} and $PM_{2.5}$ concentration measurement methods is given in Table 1. According to this; filter-based gravimetric samplers are the PM_{10} reference measurement method according to EN 12341 and EPA 40 CFR PART 50 and EU directives, and chemical analyses of the measurement results are performed. However, this method is costly and measurement values are obtained from laboratory results. On the other hand, measurement results can be obtained in a short time (< 1 hour) with real-time monitoring techniques. Only PM_{10} sampling with the BAM method, one of the real-time monitoring techniques, complies with EU directives.

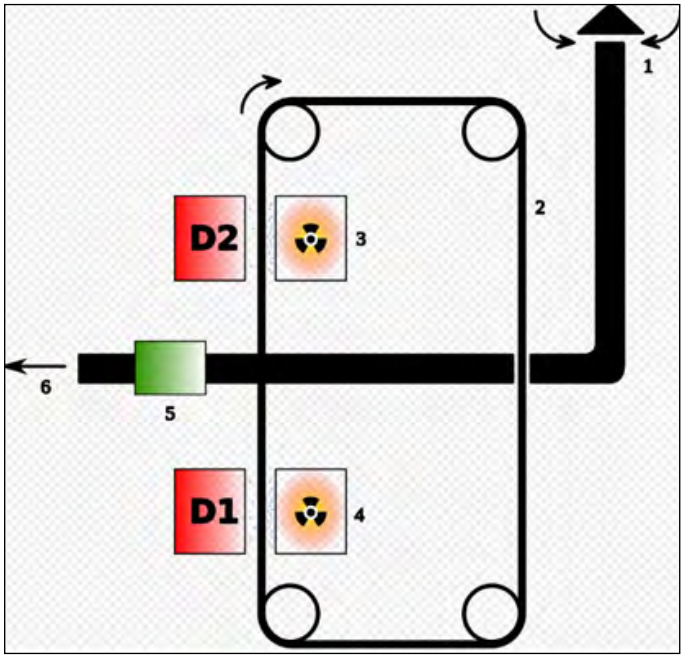

Figure 3. Working diagram of a BAM analyzer "1. "Air intake, 2. Bicycle lane, 3 and 4. Beta radiation source, D1 and D2 Beta radiation detectors, 5 air pumps, 6. Air exhaust" (Url-4, 2023)

1.5. PM related standards

Determination of PM_{10} mass concentration in ambient air is made in accordance with EN 12341 or EPA 40 CFR PART 50, $PM_{2.5}$ mass concentration in accordance with EN 14907. According to the European Union First Air Quality Directive (1999/30/EC), PM_{10} measurements should be made using the reference method as defined in the EN 12341 European Standard. This standard includes "very high volume sampler-WRAC", "high volume sampler-HVS" (PM_{10} sampler-1133.33 L/min) and "low volume sampler-LVS" (PM_{10} sampler-38.33 L/min). It recommends three sampling devices: very high volume samplers are often considered the 'primary standard' and are not suitable for placement in general work environments (Pilling et al., 2005). When the literature was examined, it was seen that low volume samplers were frequently used. According to this standard, the measurement period, the laboratory temperature for filter weighing and humidity should be 24 hours, 19-21 °C and 45-50% (TSE EN 12341, 2014; Url-5, 2023), respectively. In the EPA 40 CFR PART 50, the measurement period, the flow rate of the device to be used, the laboratory temperature for filter weighing and humidity should be 24 hours,16.67 L/min, 15-30 °C and 20-45% (EPA, 1999), respectively.

Table 1. Comparison of PM10 and PM2.5 particulate matter concentration measurement methods (Pilling et al., 2005; EPA, 2008; Environment Agency, 2011; Winkel et al., 2014; Amaral et al., 2015; Walley and Zandi, 2016)

Monitoring type	Measurement technique	Standard method	Advantages	Disadvantages	Measuring range and time	Measurement accuracy ($\mu g/m^3$)
Period-average sampling	Filter-based gravimetric samplers	i. EN 12341 ii. EPA 40 CFR PART 50	i. PM10 reference measurement method according to EU directives ii. Chemical analysis can be done as a result of the measurement	i. Measurement cost is high. ii. Measurement time is limited to 24 hours. iii. It does not meet the reporting requirements of EU directives. iv. The measurement result is obtained after the laboratory results.	Measuring time 24 hours and volumetric flow 16.67 l/min	± 2
Real-time monitoring	Conical element oscillating micro balance (TEOM)	i. Standard TEOM does not meet the equivalence criteria in the EU reference method for PM_{10} (EN12341) or $PM_{2.5}$ (EN14907). ii. Many government agencies in the USA have adopted the equivalent method for measuring PM_{10}.	i. Real-time data reading can be done for short periods of time (<1 hour), which users can easily see. ii. Measurement accuracy is better than the reference method.	i. The preheated airflow causes greater semivolatile loss compared to the reference method. ii. Measurement cost is high. iii. The expanded uncertainty in the limit value for PM_{10} and $PM_{2.5}$ exceeds 25%. iv. The filter should be replaced when the PM concentration is high. v. Filter life is 2 - 4 weeks.	0-5000 mg/m^3	± 0,5
Real-time monitoring	Beta ray attenuation (BAM)	i. Some models comply with EN12341 without correction factors, some with correction factors. ii. PM_{10} measurement complies with EU directives, $PM_{2.5}$ does not.	i. Real-time data reading can be done for short periods of time (<1 hour), which users can easily see. ii. Measurements are semi-continuous and provide hourly results, not instantaneous.	i. If heated inlet is used, some semi-volatile PMs may be lost. ii. Unheated samplers may have reduced flow due to the presence of water. iii. The analyzer contains a radioactive source.	0-1000 $\mu g/m^3$	± 3, but this value depends on the analyzer.
Real-time monitoring	Luminescent optical particle counter (Nephelometer)	i. It measures in accordance with some standards (CEN-TR 16013-3) in England. There are currently no CEN, ISO or BS standard methods covering this technique.	i. PM_{10}, $PM_{2.5}$ and PM_1 measurement can be done simultaneously. Stationary and portable versions are available. ii. The number of particles present in different size ranges is measured and mass concentrations can be derived mathematically using a density factor.	i. It is not suitable for the popular automated method of scanning surveys that consistently gives real-time results. ii. The PM magnitude during measurement is affected by shape, color and refractive index. iii. The accuracy rate is 30%. iv. The optics inside the meter may become contaminated with PM. v. Because the calibrated PM used to check the accuracy of the PM measurement differs from the measured PM, actual concentration readings may be seriously underestimated or overestimated.	Varies by analyzer. 0-6000 $\mu g/m^3$	Depends on analyzer type.

The European Standard EN 12341 is defined as the TSE EN 12341 in Türkiye as "*Ambient air - Standard gravimetric measurement method for the determination of PM_{10} or $PM_{2.5}$ mass concentrations of suspended particulate matter*". The original version of this standard (EN 12341: 2014) was prepared by the technical committee CEN/TC 264 "Air quality", whose secretariat is managed by DIN. This standard also replaces EN 12341:1998 and EN 14907:2005. This standard can also be used to calculate mass concentrations of other PM fractions such as PM_1. According to this standard, measurements are carried out with samplers operating at a nominal flow rate of 2.3 m^3/h during a nominal sampling period of 24 hours, with inlet designs as specified in Annex A of the standard, and measurement results are expressed in $\mu g/m^3$. The range of application of this European Standard is from approximately 1 $\mu g/m^3$ (i.e. the limit of observability of the standard measurement method expressed in terms of the uncertainty of the method) to 150 $\mu g/m^3$ for PM_{10} and 120 $\mu g/m^3$ for $PM_{2.5}$. Here, ambient air is passed at a constant flow rate through a known size selective inlet and the relevant PM fraction is collected in a strainer for a known period of nominal 24 hours. The mass of the PM material is determined by weighing it with a strainer at pre-specified constant conditions before and after collecting the particulate matter, hence the concentration in micrograms per cubic meter ($\mu g/m^3$) in the measured environment. It is then calculated by dividing the difference between sampled and unsampled filter masses by the sample volume found by multiplying the flow rate and sampling time as given in Equation 4.

$$c = (m_1 - m_u)/(Q_a * t) \quad (4)$$

Where;

c : Concentration per cubic meter ($\mu g/m^3$)

m_1 : Sampled strainer mass (μg)

m_u : Unsampled filter mass (μg)

Q_a : Flow rate at ambient conditions (m^3/h)

t : Sampling time (h)

When using sampling systems operating at flow rates other than 2.3 m^3/h, the strainer conditioning and weighing requirements can be obtained in accordance with standard's Clause 6 by applying a scaling factor equal to the ratio of the flow rates of the non-reference and reference samplers. Accordingly, for a sampler operating at a flow rate of 30 m^3/h, the scaling factor of the filter witnesses is considered to be equal to 30/2.3 (TSE EN 12341, 2014). On the other hand, monitoring of aerosols in workplaces and evaluation of particle concentrations in the air can be done in accordance with the CEN/TR 16013-3:2012. This standard details the use of photometers (aerosol monitors) for the determination of airborne particles of the respirable fraction, their measurement limitations and their possible use in the field of occupational hygiene. All photometer-based direct reading aerosol monitors use the principle of light scattering to determine airborne particle concentration (NSAI, 2012). Studies carried out to estimate PM emission rates resulting from activities in open-pit mining operations and the devices used in measurements are given in Table 2. It has been noted that most studies on PM emissions are conducted on coal mines; whereas, little research has been done on iron, manganese, and copper mines, as well as gypsum and limestone quarries. However, measurements of PM emissions have only been discovered in the aforementioned open-pit mines. Measuring of PM_{10}, $PM_{2.5}$, and TSP emissions was mostly done for routine operations including drilling, loading, and hauling. PM_1 emission levels were the lowest measured. The majority of the indicators measured were meteorological, aside from PM emissions. Thermal comfort and PM emission tests were conducted using various brands and kinds of instruments.

2. Open pit PM emission measurements

It is crucial to estimate PM emissions for comparable activities and to compute the PM emissions from open pit mining operations in a realistic manner in order to regulate air quality. Activity based emissions must be continuously measured and tested with various parameters. Various researchers have used different parameters to estimate PM (TSP, PM_{15}, PM_{10}, $PM_{2.5}$ and PM_1) emission rates resulting from activities during open-pit mining operations. Studies on basic activities such as drilling, blasting, loading and hauling in the mining industry have been compiled. The parameters used by the PM emission estimation equations, handled formations, and particulate matter emission were analyzed in the following sections.

2.1. PM emission from drilling operations

There have been nine studies conducted to estimate PM emissions from drilling operations. The majority of research has focused on TSP estimate (64%) while none has examined PM_{15} estimation (0%) (PM_{10} → 18%, $PM_{2.5}$ → 9% and PM_1 → 9%). Parameters such as moisture and silt content of the drilled formation, wind speed, hole diameter and drilling frequency (Chakraborty et al., 2002; Lal and Tripathy, 2012), moisture and silt content of the drilled material (Nagesha et al., 2016) were employed in the modeling of TSP emission during drilling operations in the overburden layers of open coal mines. Furthermore, during coal drilling, a TSP release rate of 0.1 kg/hole was utilized (USEPA 1998), and during coal pickling, a constant value of 0.59 kg/hole (USEPA 1998; NPI, 2012) was employed. A constant value of 0.31 kg/hole for PM_{10} was utilized in coal mine research (NPI, 2012). On the other hand, air temperature, relative humidity, station pressure, dew point temperature, wind speed (including side and counterwind speeds), silt + clay content of the material, and material moisture were used in TSP, PM_{10}, $PM_{2.5}$, and PM_1 emission modeling that was done in gypsum and limestone quarries (Duran, 2022). Examining the literature, TSP release prediction models considered hole diameter and drilling frequency the least, and the moisture content of the drilled material and wind speed the most. Factors such air temperature, relative humidity, station pressure, dew point temperature, wind speed (including head and side wind speed), silt + clay content of the material, and material moisture were utilized to estimate PM_{10}, $PM_{2.5}$, and PM_1 emissions (Figure 4).

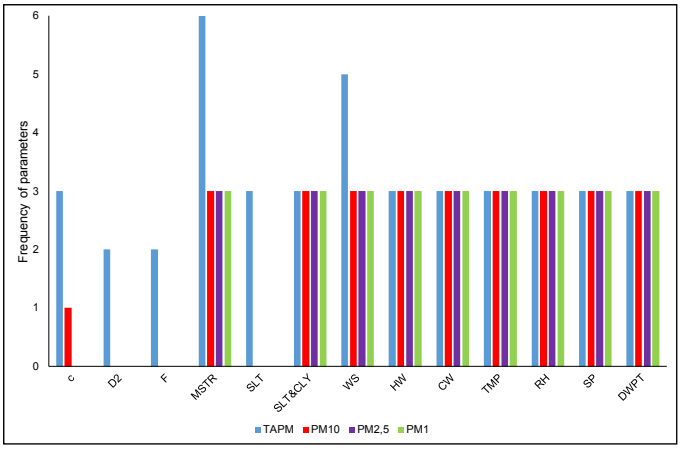

Figure 4. Frequency of parameters used for estimating PM emissions from drilling operations

Table 2. PM release measurements in open mining operations

Author, year	Study area	Remark	Parameter	Instruments
Chakraborty et al., 2002	Drilling, Coal/mineral loading Overburden loading and unloading Haul road and Transport Road Exposed overburden dump Stock yard, Exposed pit surface Coal handling plant Workshop, Overall mine (for TSP)	Coal	TSP Meteorological parameters Particle size (silt content) Moisture content	High volume sampler (HVS) with an average flow rate 1.1 m^3/min (Model: APM 415 Envirotech Instruments Pvt. Ltd) Automatic Digital Weather Monitoring Station, OMNIDATA International, USA Sieve (mesh 4 mm, 2 mm, 125 µm and 75 µm) Oven and electronic balance (Mettler)
Chaulya, 2006	Waste loading and unloading Iron ore loading Haul and Transport Road	Iron	TSP	High volume sampler (HVS) with an average flow rate higher than 1.1 m^3/min (Model: APM 415 Envirotech Instruments, New Delhi, India and measurement by Digital Electronic Balance Mettler, Switzerland)
Lal and Tripathy, 2012	Drilling and Overburden loading Coal handling (Feeder Breaker) Haul road and Transport Road OB unloading and Railway siding Exposed OB Dumps, Coal loading	Coal	TSP Meteorological parameters	Air quality monitoring Meteorological Department
Aneja et al., 2012	Transport road	Coal	PM_{10}	Andersen/GMW Model GUV-16H high volume air samplers
Badu, 2014	Shovel-Loading, Surface Miner Drilling, Wet Haul Road Transportation Road OB Bench (Before blasting) OB Bench (After first blasting) OB Bench (After second blasting)	Coal	PM_{10} PM_4 $PM_{2.5}$ PM_1	DustTrak II Aerosol Monitor (Model No - 8532)
Huertas et al., 2014	Pit, Beltway, Dump and Stock Pit-dump via and Pit-stock via	Coal	TSP Meteorological parameters	Monitoring station Meteorological stations
Kishore, 2015	Surface mine environment	Iron Manganese	TSP, PM_{10} Meteorological parameters	Envirotech APM 460 NL Meteorological stations
Gautam and Patra, 2015	Open-pit mine	Copper	PM_{10}, $PM_{2.5}$ and PM_1 Meteorological parameters	Grimm aerosol spectrometer (Grimm, model 1.108) Portable weather station (Spectrum Technologies, Inc., Model Watchdog 2000)
Gautam et al., 2015	Open-pit mine	Iron	PM_{10}, $PM_{2.5}$ and PM_1 Meteorological parameters	Grimm aerosol spectrometer (Grimm, model 1.108) Portable weather station (Spectrum Technologies, Inc., Model Watchdog 2000)
Lashgari and Kecojevic 2015	Overburden loading by cable shovel Overburden loadind by front-end wheel loader	Coal	TSP, PM_{10}, PM_4, $PM_{2.5}$ and PM_1 Meteorological parameters	TSI DustTrak DRX 8534 real-time aerosol monitoring instrument. Kestrel 4500 Weather Meter
Sastry et al., 2015	Drilling	Coal	PM_{10} $PM_{2.5}$ Meteorological parameters	Personal dust monitors/Dust dosimeter (5 units) Point samplers (2 units) Meteorological monitoring station
Tripathy et al., 2015	Shovel-dumper, Surface miner Drilling, Wet haul road Transportation road Office of colliery manager OB bench (before blasting) OB bench (after blasting 1) OB bench (after blasting 2)	Coal	PM_{10} PM_4 $PM_{2.5}$ PM_1	DustTrakII
Nagesha et al., 2016	Drilling	Coal	PM_{10}	Ambient point samplers

Author, year	Study area	Remark	Parameter	Instruments
			Meteorological parameters Moisture content Particle size (silt content)	Meteorological station
Patra et al., 2016	Open-pit mine	Copper	$PM_{0.23 - 0.3}$, $PM_{0.3 - 0.4}$, $PM_{0.4 - 0.5}$ $PM_{0.5 - 0.65}$, $PM_{0.65 - 0.8}$, $PM_{0.8 - 1.0}$ $PM_{1.0 - 1.6}$	GRIMM aerosol spectrometer (Model 1.108, Grimm)
			Meteorological parameters	Portable weather station (Spectrum Technologies, Inc., Model Watchdog 2000)
Oudwater, 2017	Drilling	Stone quarry	PM_{10}	Turnkey Osiris nephelometer
Wanjun and Qingxiang, 2018	Open-pit mine	Coal	PM_{10} and $PM_{2.5}$	The beta-ray particle monitor
Sahu et al., 2018	Surface coal mine environment	Coal	PM_{10}, $PM_{2.5}$ and PM_1	Grimm aerosol spectrometer (Model 1.108, GRIMM Aerosol Technik GmbH & Co. KG, Germany)
			Meteorological parameters	Portable weather station (Spectrum Technologies, Inc., Model Watchdog 2000)
Richardson et al., 2018	Product stockpile Coal loading, hauling, dumping Topsoil spreading Dragline on overburden Pre-strip Coal preparation plant Dumping into coal hopper Drill Spontaneous combustion Shovel Dozer	Coal	TSP, PM_{10} and PM_2	Optical-Grimm model 1.105
	Mine haul road Product stockpile Background position representing nearest receptor Product stockpile and mine processing area Operating mine as a whole		PM_{10} and $PM_{2.5}$	Gravimetric MiniVol (high-volume sampler)
Tripathy and Dash, 2019	Open-pit mine	Coal	PM_{10} and $PM_{2.5}$	Envirotech APM 460 NL
Richardson et al., 2019	Coal haul road Overburden haul road Drilling, Dragline Overburden loading and dumping Coal loading and dumping	Coal	$PM_{2,5}$	Met-One E-Bam, fitted with US EPA approved reference $PM_{2,5}$ cyclone separator TSI DustTrak model 8530
			Meteorological parameters	Davis weather station for initial stage of sampling. Met-One 034B Windset coupled with a Campbell Scientific CR800 data logger
			Soil moisture and silt content	Calibrated laboratory oven and soil sieve set
Bui et al., 2019	Drilling	Coal	PM_{10}	KANOMAX digital dust monitor model 3442
Luo et al., 2021	Mining area	Coal	TSP, PM_{10} and $PM_{2.5}$ Meteorological parameters	RS-ZSYC-9S-4G multi-parameter monitoring device
Duran, 2022	Drilling Loading Transport road	Gypsum Limestone Quarries	TSP, PM_{10}, $PM_{2.5}$ and PM_1 Particle size (silt content) Moisture content	DustMate environmental monitor Sieve (216 µm, 150 µm, 106 µm and 75 µm) Vibratory Sieve Shaker AS 200 Binder Etuv
			Meteorological parameters	Kestrel 5500 Weather Meter

2.2. PM emission from blasting operations

To quantify PM emissions from blasting activities, nine studies have been undertaken. The majority of research has focused on TSP prediction (43%), whereas no research has targeted on PM_1 prediction (0%) (PM_{15} → 10%, PM_{10} → 33%, $PM_{2.5}$ → 14%). TSP emission during blasting activities in the overburden layers of open coal mines was modeled using factors such as blast area, blast hole length, and moisture of the blasted material (Axetell and Cowherd 1984; USEPA, 1998; NPI, 2001-2012) and blast area alone (USEPA, 1991-1995-1998; NPI, 2001-2012). USEPA (1991-1995-1998) and NPI (2001-2012) multiplied PM_{10} by a fraction (0.52) of TSP in order to model PM_{15} emissions whereas TSP was multiplied by a coefficient of 0.03 to yield $PM_{2.5}$ (Axetell and Cowherd 1984; USEPA, 1998). The blasting area was the most important factor for TSP emission models, whereas the moisture content of the blasted material and the hole size were the least important factors. The blasting area, hole length, and moisture content of the blasted material were all employed in identical numbers for the PM_{15} emission models. Models for PM_{10} and $PM_{2.5}$ emissions were produced by simply multiplying TSP by a certain coefficient (Figure 5).

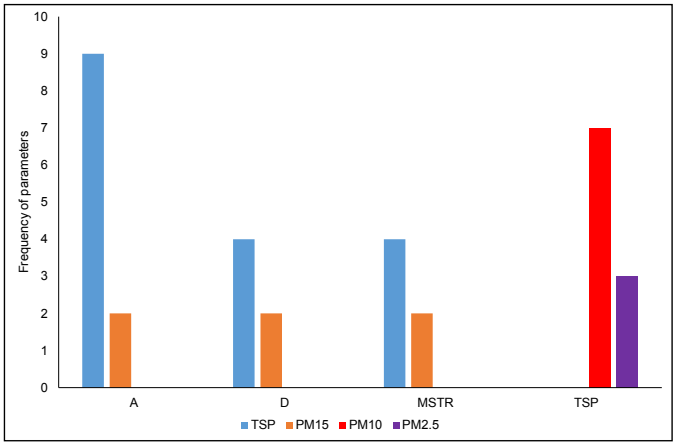

Figure 5. Frequency of parameters used for estimating PM emissions from blasting operations

2.3. PM emission from loading operations

Sixteen research studies have been conducted to estimate PM emissions during loading activities. When the studies on PM estimation are weighted as a percentage, the rate of PM_1 estimation was 3%, whereas the rate of TSP estimation was 44% (PM_{15} → 15%, PM_{10} → 19%, $PM_{2.5}$ → 19%). Parameters like the moisture content of the loaded material (Axetell and Cowherd 1984; USEPA, 1991-1995-1998; NPI, 2012), and the moisture and silt content of the loaded material, material unloading height, wind speed, loading frequency, and loader capacity (Chakraborty et al., 2002; Lal and Tripathy, 2012) were used in the modeling of TSP in loading operations in open coal mines. The modeling of TSP emission during pickling in coal mines took into account moisture and silt content of the loaded material, material unloading height, wind speed, loading frequency and loader capacity (Chakraborty et al., 2002; Lal and Tripathy, 2012) and moisture content and wind speed of the loaded material (NPI, 2012). The TSP generated during ore production and stripping in an open iron mine was modeled using the following factors: wind speed, load frequency, moisture and silt content of the loaded material, material unloading height, loader capacity, and loading frequency (Chaulya, 2006). In aggregate quarries, factors including material moisture content and wind speed (USEPA, 2006) were taken into account in loading operations. Parameters including moisture content of the loaded material (NPI, 2012), moisture content of the loaded material and wind speed during coal pickling (NPI, 2012), and correction factors (0.75*PM15) (USEPA, 1991-1995) were considered while predicting PM_{10} emission in coal production. Similarly, PM10 in aggregate loading was estimated using 0.35*TSP. An equation of 0.053*TSP for aggregate loading (USEPA, 2006) and 0.019*TSP for coal production (Axetell and Cowherd 1984; USEPA, 1991-1995-1998; NPI, 2012) was used for estimating $PM_{2.5}$ emissions. TSP, PM_{10}, $PM_{2.5}$, and PM_1 emissions in gypsum and limestone quarries were predicted using parameters such as air temperature, dew point temperature, station pressure, relative humidity, wind speed (including counter and side wind speed), humidity of the loaded material, and loader bucket volume (Duran, 2022). Based on a review of pertinent literature, the moisture content of the material being loaded, wind speed, loader bucket volume, unloading height, and loading frequency are the main factors used in TSP emission models; at the very least, counter and side wind speeds, air temperature, station pressure, relative humidity, and dew point temperature are considered. Loader bucket volume, material moisture, wind speed (including head and crosswind speeds), air temperature, dew point temperature, relative humidity, and station pressure were all employed in PM1 emission models (Figure 6).

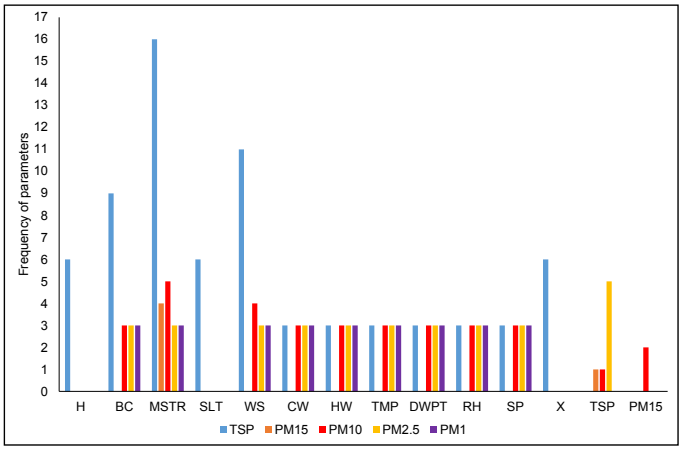

Figure 6. Frequency of parameters used for estimating PM emissions from loading operations

2.4. PM emission from hauling operations

For hauling both within and outside the pit, twelve studies yielded PM emission models. 48% of the research concentrated on TSP estimate and 4% on PM_1 estimation (PM_{15} → 10%, PM_{10} → 21%, $PM_{2.5}$ → 17%). The following parameters were used for TSP emission modeling in open coal mines for in-pit transportation; truck mass and silt content of the road surface (Axetell and Cowherd 1984; USEPA, 1991-1998); silt content, truck mass and moisture content (NPI, 2001); moisture and silt content, wind speed, average truck speed, vehicle cycle frequency and truck capacity (Chakraborty et al., 2002; Lal and Tripathy, 2012); moisture, silt content and average truck speed (NPI, 2012). In the modeling of TSP emission for an open iron mine, Chaulya (2006) profited from moisture and silt content, wind speed, average truck speed, vehicle frequency, and truck capacity. Another method used truck mass and silt content to achieve stabilized road conditions (USEPA, 2006). Furthermore, moisture and silt content, wind speed, average truck speed, and vehicle cycle frequency were employed for TSP emission modeling in hauling operations on the main haul

roads in coal and iron mines (Chakraborty et al., 2002; Lal and Tripathy, 2012; NPI, 2012). For in-pit roads of open coal mines, the formula 0.60*TSP has been suggested for PM_{10} estimation (USEPA, 1991). Modeling of PM_{10} emissions from gravel roads took into account truck mass, moisture, and silt content (NPI, 2001); moisture, silt content, and average vehicle speed (NPI, 2012) and silt content and truck mass (USEPA, 2006). For coal mine main haulage roads silt content and truck mass were considered (NPI, 2012). On a stabilized road, an equation of $0.1*PM_{10}$ is introduced to estimate $PM_{2.5}$ emissions (USEPA, 2006). Air temperature, dew point temperature, station pressure, relative humidity, wind speed (including counter and side wind speed), moisture and silt + clay content of the road material, truck mass, number of wheels, and truck speed were used for TSP, PM_{10}, $PM_{2.5}$, and PM_{1} emission modeling in gypsum and limestone quarries (Duran, 2022). The moisture and silt content of the haul road material, truck mass, and vehicle speed are the most commonly used parameters for TSP emission models, while the counter and side wind speeds, air temperature, station pressure, relative humidity, dew point temperature, number of truck wheels, a specific coefficient, and silt+clay content are the least commonly used ones. Only truck mass was used to build PM15 emission models. For PM_{10} emission models, the highest value was obtained when truck mass and vehicle speed were taken into account, while the lowest value was reached by multiplying TSP with a certain coefficient. Air temperature, dew point temperature, station pressure, relative humidity, wind speed (including head and side wind speed), moisture and silt+clay content of road material, truck mass, number of truck wheels, and vehicle speed were all employed in PM2.5 and PM1 emission models (Figure 7).

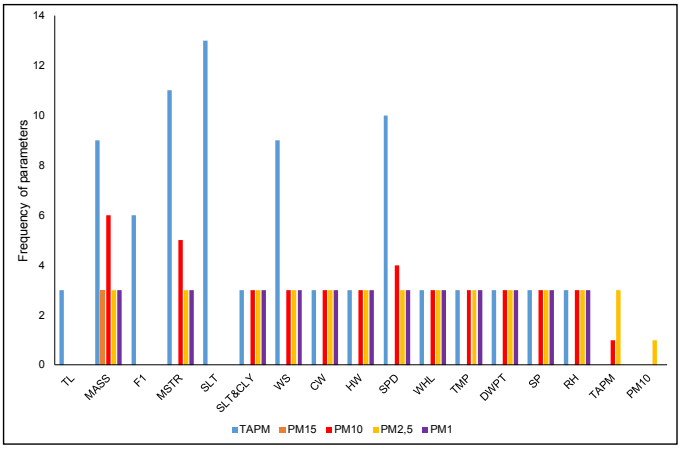

Figure 7. Parameters used in transport activity PM release estimates

3. Conclusions

In this paper, previous research has been compiled on the monitoring and the prediction of PM emissions considering basic open-pit mining activities such as drilling, blasting, loading, and hauling. 69.6% of the research on PM emission measurements and projections were conducted in coal mines, whereas only 30.4% were conducted in iron, manganese, copper mines, and gypsum and limestone quarries. Nevertheless, other than the open-pit mines mentioned above, no measurements of PM emissions have been reported in the literature. This requires that further researches should be carried out in other fields of mining than coal. The majority of the articles reviewed in this field measured PM_{10}, $PM_{2.5}$, and TSP emissions, with PM_{4} emissions being the least. In terms of quantification, 78.26% of the articles had measurements of PM_{10}, 56.52% of $PM_{2.5}$, 39.13% of TSP, 30.43% of PM_{1}, and 13.04% of PM_{4}. Other emission rates were also estimated and the equations developed, primarily utilizing TSP and PM_{10} data. Similar to PM emission, a variety of brands and models of instruments were used to measure meteorological factors. It was found that, even for the same mining activity and for the same location, the equations used for PM emission prediction might create or produce different results. Therefore, it would be appropriate to design or develop prediction models that are unique to the mine in question.

Nomenclature

A	: blasting area (ft^2, m^2)
BC	: Loader bucket volume (m^3)
c	: Constant
CW	: Side wind speed (m/s)
D	: Blasting hole length (ft, m)
DWPT	: Dew point temperature (°C)
D2	: Hole diameter (mm)
F	: Drilling frequency (number of holes/day
F1	: Vehicle frequency (number/hour)
H	: Material unloading height (ft, m)
HW	: Headwind speed (m/s)
MASS	: Truck mass (t)
MSTR	: Moisture content (% mass)
RH	: Relative humidity (%)
SLT	: Silt content (%)
SLT&CLY	: Silt content (%)
SP	: Station pressure (mb)
SPD	: Truck speed (km/h)
TMP	: Air temperature (°C)
TL	: Truck capacity (t)
WHL	: Number of truck wheels (pieces)
WS	: Wind speed (m/s)
X	: Upload frequency (number/hour)

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