UNIVERSITY OF NAIROBI

ASSESSMENT OF AIRBORNE PARTICULATE MATTER AROUND CEMENT INDUSTRIES IN ATHI RIVER, MACHAKOS COUNTY, KENYA

BY

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DECLARATION

I declare that this thesis is my original work and has not been submitted elsewhere for examination. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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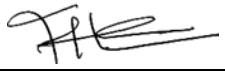
Signature:  Date: 7th June 2021

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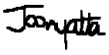
Signature:  Date:7th June 2021

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DEDICATION

This thesis is dedicated to my family and to all those who supported me in the course of my study to make it a success.

ABSTRACT

Particulate matter (PM) of 10 micron (μm) or less in diameter, (PM_{10}) is a component of inhalable dust. These particles are indicators of air pollution and one of the major human health and environmental concern. Their harmful health effects, ranges from minor irritation to chronic infections in the respiratory system. Furthermore, their toxicities depend on the chemical composition. The PM_{10} levels vary greatly due to the influence of meteorological factors and their removal from the atmosphere is most challenging especially when they consist of secondary particles. There has been health concern among communities over possible exposure to elevated levels of PM_{10} of the cement industries. The study was therefore conducted to assess PM_{10} levels around the cement industries in Athi River Municipality, Machakos County in Kenya. The PM_{10} levels were collected from five sites in the morning and afternoon for three hours at each site, for three consecutive days during the rainy (April-June and in October) and dry (January-March and in September) seasons of 2019. They were collected using a 47 mm polytetrafluoroethylene filter membrane fitted in an air sampler (Model: Ecotec microvolt-1100). All filter membranes were conditioned for 24-hours prior to pre-weighing and post-weighing using unibloc shimadzu AUW220D analytical balance. Meteorological measurements were further recorded during collection of PM_{10} levels. The analysis of PM_{10} levels and elemental composition were carried out using the gravimetric and energy dispersive X-ray fluorescence (EDXRF) techniques, respectively. The results showed that mean ± standard deviation (SD) PM_{10} levels ranged from 43.2±10.7 to 592.6±133.5 $\mu g/m^3$ across the five sites regardless of the period of the day and the season. In descending order, the industrial site "A" had mean PM_{10} level ($\mu g/m^3$) of 592.6±133.5 and 271.6±46.6; industrial site "B" had 401.2±70.1 and 216.0±28.3; commercial site had 370.4±49.0 and 160.5±38.6; residential areas "B" had 333.3±37.1 and 179.0±10.7 and "A" had 246.9±21.4 and 129.6±18.5 in the morning and afternoon, respectively during the dry season. During the rainy season, similar trends were observed with industrial site "A" having a mean PM_{10} level ($\mu g/m^3$) of 302.5±56.6 and 166.7±37.1; industrial site "B" had 277.8±32.1 and 154.3±28.3; commercial site had 246.9±46.6 and 86.4±21.4 residential areas "B" had 197.5±38.5 and 74.1±18.5 and "A" had 111.1±18.5 and 43.2±10.7, in the morning and afternoon, respectively. The study showed that industrial sites had the highest PM_{10} levels, followed by the commercial sites and the least levels were from residential sites. The substantial PM_{10} levels in these sites were mainly attributable to emissions from cement industries. The levels were significantly higher ($p< 0.05$) in the morning than afternoons in both seasons and considerably high ($p < 0.05$) during the dry compared to the rainy season. The meteorological factors had a high influence ($p < 0.05$) on these levels where, negative correlations of R= -0.752 and R= -0.783 were observed between wind speed and temperature, respectively, and PM_{10} levels during the dry season. Conversely, a positive correlation of R = 0.906 was obtained between relative humidity and PM_{10} levels. Similar trend in the correlation values of R = -0.374, R = -0.506 and R = 0.826 were observed between wind speed, temperature and relative humidity, respectively, and PM_{10} levels in the rainy season. The mean PM_{10} values for residential site ''B" situated downwind of the cement industries were also consistently high notwithstanding the period of the day and season when compared to those of the residential site "A" situated upwind. The PM_{10} levels at the five sites had variations in the percentage composition of Cu, Sb, Si, Al, Ca, Fe, Zn, Cr, Pb, Cd and Ni. Nonetheless, Si, Cd, Al, Ca and Fe, components of cement, were prominent elements detected across these sampling sites irrespective of the seasons. The high levels of PM_{10} with toxic components found in this study implies that suitable interventions and policies should be put in place to control these levels and safeguard human health and environment.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAQ	Ambient Air Quality
AQ	Air Quality
ANOVA	Analysis of variance
AQGS	Air Quality Guidelines
BDL	Below Detection Limit
BS	British smoke/Black smoke
EU	European Union
GPS	Global positioning system
NEMA	National Environmental Management Authority
QA/QC	Quality Assurance/Quality Control
PC	Personal computer
PM	Particulate matter
PM_{10}	Particulate matter with cut- off diameter equal to or less than 10μm
$PM_{2.5}$	Particulate matter with cut- off diameter equal to or less than 2.5μm
PTFE	Polytetrafluoroethylene
RH	Relative humidity
ROS	Reactive oxygen species
SPM	Suspended particulate matter
TSP	Total suspended particles
$\mu g/m^3$	Microgram per cubic meter
μm	Micrometers
US EPA	United States Environmental Protection Agency
WHO	World Health Organization.

CHAPTER ONE

INTRODUCTION

1.1: Background information

Air pollution is the presence of complex mixtures suspended in the atmosphere that bring about damage to the well-being of humans and the environment as stated by US EPA (1998). The term air pollutant is used to describe chemicals or compounds in the atmosphere from either an anthropogenic or natural source. These pollutants have significant long-term and short-term effects to human health and environment depending on their concentration (Abdullah and Iqbal, 1991). Primary pollutants are substances that are directly emitted to the atmosphere from a source for example ash from volcanic eruption. Secondary pollutants on the other hand are released incidentally to the atmosphere. The latter are synthesized to form aerosols from the reactions involving other pollutants such as oxides of nitrogen that are transformed into ozone. Particulate matter in the atmosphere causes unhealthy air quality which affects the environment and human health (Gauggel-Lewandowski *et al*., 2013).

Atmospheric aerosols are of great importance in Earth's climatic system in such a way that they increase cloud droplets that reflect the solar radiation hence influencing the colour of the clouds (IPCC, 2013). Dark aerosols absorb notable amounts of light. In addition, pure sulphates and nitrates reflect almost all radiation they interact with, thereby lowering temperatures in the atmosphere. Human activities are major sources of pollutants found in the ambient air that occur in dust and gaseous form. Persistent air pollution in the environment as a result of excessive release and emission of toxic chemicals is also influenced by the meteorological and topographic conditions (Aydn and Kavraz, 2011).

Particulate matter is a complex blend of microscopic solid and liquid particles that are suspended in the atmosphere and are usually harmful to human and environment. Their characterization mostly depends on their size, composition or origin. Ambient particulate matter is classified in terms of aerodynamic diameter that include; total suspended particles (TSP) made of all types of aerosols of diverse sizes. Additionally, PM_{10} particles are equal or less than 10 micron (um) in diameter, while $PM_{2.5}$ are equal to or less than 2.5 um in diameter whereas $PM_{1.0}$ particles are equal to or less than 1 um in diameter (Nel, 2005). The former is depicted in terms of inhalable particles and associated with unhealthy air quality for human beings. Natural processes are the major sources of coarse particles ($PM_{2.5-10}$) in form of dust storm while anthropogenic sources include various industrial emissions (Querol *et al*., 2004). Fine particles ($PM_{0.1-2.5}$) generally encompasses organic and elemental carbon, ammonium, sulphate, nitrate, and metals (Li *et al*., 2004). Ultrafine particles ($PM_{0.001-0.1}$) include diesel exhaust particles that come from automobiles (Bujak-Pietrek *et al*., 2016).

Cement manufacturing is a hazardous process that is not only associated with combustion of fuels resulting in emission of oxides of carbon and other greenhouse gases, it is also linked with emission and release of particulate matter (IPCC, 2013). Raw materials, the entire production process including the finished products from cement factories generate substantial PM_{10} levels which is considered as an air pollutant. These particles that are released through production processes, range from handling to transportation hence damaging the environment and have profound effects on human health. Ultimately, all the stages of production line are responsible for the emission of particles and they include; quarrying, crushing, grinding, calcination, cooling, blending, milling, storage and bagging of cement.

Nevertheless, cement is a necessary ingredient for economic development in a country since it supports most of the infrastructure. Utilization of cement in concrete and as a primary binding agent, makes it a building block in the construction industry. Its production and utilization are therefore highly correlated with economic performance of a country. Kenya has experienced consumption of cement in an upward trajectory over time. The manufacture of cement primarily involves mechanical processes that result in generation of large quantities of aerosols in the environment. The particles have been associated with mortality as well as cardiovascular and respiratory diseases (Roberts *et al*., 2013). Availability of data on the particulate matter is a good pointer of air quality monitoring capabilities. This can be achieved through continuous assessment of PM_{10} and $PM_{2.5,}$ which is recognized as an indicator of human exposure (WHO, 2017).

Extensive research has been conducted in various cities around the world concerning PM_{10} concentrations and its health effects (Roberts *et al*., 2013). Recent literature on composition of PM_{10} had suggested that heavy metals and carbon compounds play an important role in particle toxicity (Lippmann, 2010). Clinical and toxicological studies had shown a relationship between PM_{10} and quite a range of human health effects (Araujo, 2011). PM_{10} has therefore been acknowledged as a significant public health problem across different regions of the world, as it is an important indicator of human exposure to pollutants in majority of the studies (WHO, 2006). It is considered as a representative of particulate matter that penetrates through the respiratory tract causing various health outcomes. Adverse health effects due to PM_{10} exposure show variations but mostly affect the respiratory and cardiovascular systems (WHO, 2006). The inhalable dust affects all the population although the most susceptible groups are those with pre-existing diseases and children (Liu *et al*., 2018). Were *et al*. (2020) in their study also reported a higher prevalence of

relative risk and odds ratio of developing lung function abnormalities among exposed school children than those in the control groups.

1.2: Statement of the problem

Air pollution is implicated as a potent environmental and human risk factor worldwide (Pascal *et al*., 2013). Moreover, it is on the rise as a result of industrial growth and urbanization (US EPA, 2009; WHO, 2013). The PM_{10} constitute a health-relevant indicator of air quality or pollution (Karbassi *et al*., 2008). Studies have shown that concentration of pollutants associated with cement manufacturing had adverse health effects among neighboring communities (Medina *et al*., 2009). In general, the main health concern of cement industries is air pollution due to significant release and emission of particulate matter (Were *et al*., 2020). Geological materials that have been established to contribute to PM_{10} include compounds of: sodium, silicon, aluminum, zinc and iron in varying proportions, which ultimately depend on the sampling sites. Studies have further shown that particles from cement industries are usually consistent in the composition and mostly contain aluminum, silicon, calcium and iron (Chow *et al*., 1996). These particles that are 10 micrometers or less in diameter are capable of penetrating into the lungs, leading to various health problems. Respiratory health effects due to industrial pollution have also been extensively reported in communities and workers from cement industries in Machakos and Mombasa County (Birgen, 2017; Kahenya, 1996; Karue, 1991; Were *et al*., 2020).

Studies have further shown high levels of PM_{10} ranging from 111.23 to 463.31 $\mu g/m^3$ for twenty-four-hour average weighed time. These levels were emitted from cement industries to sites downwind (Shilenje *et al*., 2015). With the increase in the number of cement factories and expansion of the existing ones, the production levels have risen over time. The significant emission

and release of particulate matter is responsible for the increase in the respiratory diseases reported among school children in the same area (Were *et al*., 2020). Epidemiological studies revealed a strong relationship between elevated concentration of inhalable aerosols (PM_{10} and $PM_{2.5}$) and increased mortality and morbidity (Lin and Lee, 2004; Perez and Reyes, 2002). It is therefore necessary to monitor air quality around cement industries to safeguard the communities against adverse health effects (Acosta-Martínez *et al*., 2007; Bache *et al*., 1991).

1.3: Objectives.

1.3.1: General objective

The general objective of this study was to assess the airborne particulate matter (PM_{10}) around cement industries in Athi River municipality, Machakos County, Kenya.

1.3.2: Specific objectives

The specific objectives of this study were:

i) To determine the concentration of PM_{10} in selected sites of commercial, residential and industrial areas around cement manufacturing industries in Athi River area, Kenya during dry and rainy seasons

ii) To determine meteorological factors that influence concentration of PM_{10} in selected sites

iii) To determine the elemental composition of PM_{10} in selected sites using XRF.

1.4: Justification and significance of the study.

The World Health Organization (WHO) indicated that the mortality rate of about 2.4 million people yearly is as a result of air pollution (Meo *et al*., 2013). Studies have shown correlations between inhalable particulate matter and diseases that include; asthma, bronchitis, sore throat, chest pain, dyspnea (shortness of breath), and lung cancer (Jeff and Hans, 2004). Cement production causes the release of enormous pollutants that are harmful to human health and environment. The gases from the stack and particulate matter from the cement production are released to the atmosphere, which usually cause deterioration of the air quality and thus lead to environmental pollution (Adak *et al*., 2007).

This study is therefore aimed at determining the sources and concentration of PM_{10} in Athi River area in Machakos County where the number of cement industries are also increasing. The findings of this study would be beneficial in establishing the current status and creating awareness on ambient air quality in the area. Besides, it will open doors for further research on atmospheric aerosol pollution, mitigation measures and contribute significantly to scientific knowledge. It is expected that recommendations arising from this study will further assist in structuring of policies to not only control but also prevent emissions and release of particulate matter from the cement industries.

CHAPTER TWO

LITERATURE REVIEW

2.1: Air pollution

According to WHO (2006), pollution is any addition of matter or energy that degrades the environment. Unfavorable air quality (AQ) damages our environment which in turn impacts on plants and animals. Air pollution has remained a critical issue to be dealt with and dates back to the year 1661 when John Evelyn a diarist from England wrote fumifugium (smoak of London) about a dreadful smoke that killed both flowers and bees (Smith *et al*., 2013). The term air pollution can be defined as "a condition in the atmosphere where chemicals are present in high concentrations that exceed their normal ambient levels and generate a negative consequence on living things or materials" (Alkhdhairi *et al*., 2018). Air pollutants may exist in the atmosphere in the form of gases, liquid droplets or solid particles (Vallero, 2015).

Sources of air pollution can be classified as natural or anthropogenic. Natural sources consist of materials that can exist even in the absence of human activities. They include naturally caused forest fires, volcanoes, dust storms, pollen and spores released by plants and biological activities in the soil. Anthropogenic sources are those that are as a result of human actions. They include kiln cement, open burning of wastes, use of unclean household fuels and automobiles exhausts. Examples of air pollutants are particulate matter, oxides of nitrogen (NO_X), oxides of carbon and hydrocarbons (Levy and Hanna, 2011). Particulate matter is a liquid or solid aerosol suspended in the atmosphere. It is frequently the most obvious form of air pollution as it causes reduced visibility. Although, the range of visibility is inversely proportional to aerosols concentration. Aerodynamic diameter is usually used to characterize PM and is expressed in terms of micrometer

(μm). According to WHO (2013), inhalable particulate matter deposited in the respiratory tract causes adverse health effects in human. Inhalable particles are defined as PM whose aerodynamic diameter are equal to or less than 10 μm. It has been reported that the penetration of fine particulate matter with aerodynamic diameter equal to or less than 2.5 μm into the alveolar regions of the lungs is associated with adverse health effects (Pope and Dockery, 2006).

A study by Birgen (2017) on air pollution in Athi River, Kenya showed that levels of sulphur dioxide ranged from 602 to 861 $\mu g/m^3$ and nitrogen dioxide was 157 to 175 $\mu g/m^3$ which exceeded the recommended levels by WHO (2006). Furthermore, the study showed that the total suspended particulate matter (SPM) ranged from 670 to 4390 $\mu g/m^3$ in twenty-four-hours during both dry and rainy seasons. According to the WHO guidelines the levels of these corresponding air pollutants should not exceed 500 $\mu g/m^3$ for ten minutes' exposure and 120 $\mu g/m^3$ when exposed for 8 hours while those of SPM (< 50-100 μm) should be between 150 and 230 $\mu g/m^3$ in 24 hours (Birgen, 2017).

2.1.1: Atmospheric aerosols.

Atmospheric PM or aerosols have led to considerable poor AQ. In the past and the present trends, they have shown increasing levels across the world. Particulate matter from an environmental perspective is a crucial policy issue that deals with AQ and its contribution to climate change. In general, PM pollution is presumably the most persistent global issue when it comes to AQ regulation. Moreover, the particle size distribution of aerosols is a key determinant factor in reliability and accuracy of assessment of airborne particles that have impact on human health. This is due to their ability to penetrate deep into the respiratory tract (Kushwaha *et al*., 2013).

There are three types of particle sizes as shown in Figure 2.1.

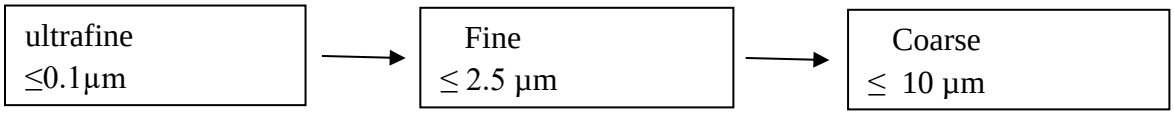

Figure 2.1: Particle Size in microns

Source: WHO, 2011.

Cement plants are often associated with particle and gaseous emissions into the atmosphere, with aerodynamic diameters ranging from 0.05 to 10 µm (Rotatori *et al*., 2015). This size is within the inhalable range and are capable of reaching the tracheobronchial tree of the respiratory system, which is the primary target of cement deposition as shown in Figure 2.2. The cement dust has therefore been implicated as a potential cause of occupational pulmonary disease among the workers in the cement industries (Rahmani *et al*., 2018).

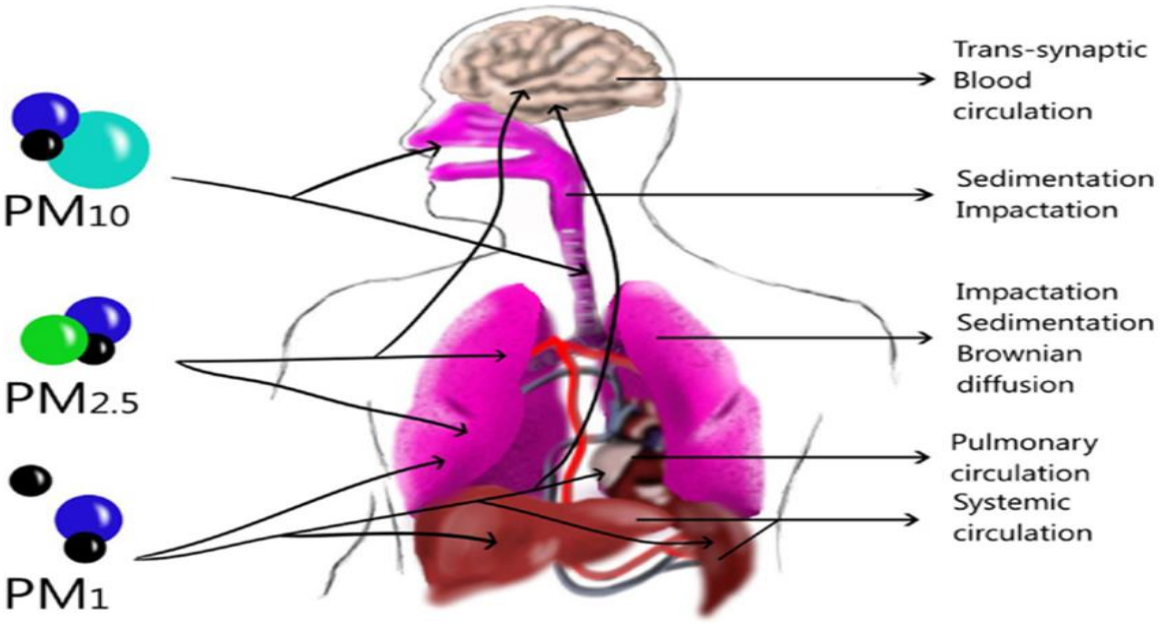

Figure 2.2: Sites for coarse and fine particles deposition in human body

Source: WHO, 2007.

The chemical composition of PM also varies and is reliant on a combination of several factors that include: sources, climate and type of urban and industrial pollution. Identifying and understanding the chemical composition of particulate matter (PM_{10}) enhances the link to their harmful effects.

2.1.2: Sources of particulate matter

PM_{10} is characterized into two aerosol types that differ in their sources with diverse physical-chemical properties. Photochemical reactions and combustion generate fine particles ($PM_{0.1\text{-}2.5}$). In contrast, coarse particles ($PM_{2.5\text{-}10}$) are normally formed through mechanical crushing or grinding and resuspension processes. The inconsistency in composition, along with the difference in deposition in the tracheobronchial tree is a clear indication that the fine and coarse particles may vary in how they impact human health.

Coarse and fine particles differ in morphologies. The information on the origin of particle and its formation have a paramount effect on human health and this can be derived from $PM_{2.5}$ /PM_{10} ratio (Wang *et al*., 2018). When $PM_{2.5}$ /PM_{10} ratio is high, the particulate matter is associated with anthropogenic source, such as cement production while smaller ratios are due to coarse particles that can be associated with natural sources like dust storms (Sugimoto *et al*., 2016). $PM_{2.5}$ /PM_{10} ratio was reported to be lower in Africa during the dry season due to resuspension of dust, and is a major contributor to PM_{10} (Akinlade *et al*., 2015). Moreover, the ratio can illustrate seasonal and diurnal variability, a study showed a ratio of more than 0.6 during the cold season (autumn-winter) while in warmer seasons (spring-summer) the ratio was less than 0.5 (Speranza *et al*., 2016). Relevant information of $PM_{2.5}$/PM_{10} ratios can predict retrospective $PM_{2.5}$ concentrations without direct measurements (Chu *et al*., 2015). It should however be noted that the value of $PM_{2.5}$ /PM_{10} ratio may vary in origin and is influenced greatly by the local conditions.

2.1.3: Human health effects due to particulate matter exposure

Health effects on humans are as a result of particulate matter (PM_{10}) being inhaled and deposited in organs of the body. Dust from cement production may cause irritation to the skin (Stocks *et al*., 2015). This is as a result of irritation of the mucous membrane caused by high pH exposure values that are attained through reaction of dust deposited in the respiratory tract (Nkhama *et al*., 2015). PM_{10} has been known to aggravate the risk of chronic obstructive pulmonary diseases (COPD) that can eventually result in death (de Matteis *et al*., 2017). Exposure to ambient PM may lead to lung cancer (Loomis *et al*., 2013). Increased mortality and morbidity have been associated with high levels of PM_{10} and $PM_{2.5}$ exposure that have been reported in most epidemiological studies (Xing *et al*., 2016, Were *et al*.,2020).

The extra-thoracic region is an entry to the human respiratory tract and acts as a natural defense against inhalable particulate matter. It includes nasal, oral passages, pharyngeal and laryngeal airways with impaction and diffusion being the main deposition mechanisms (Figure 2.2). The fugitive dust is removed through impaction in the upper respiratory tract that consists of nasal passages, paranasal sinuses and the larynx above the vocal folds. Sometimes allergic reactions and sinus ailments arise during removal of these pollutants. On the other hand, intrathoracic region consists of a part of larynx below vocal folds, trachea, bronchus and alveoli. The particles that penetrate into this region may lead to damage of the lungs and potentially transfer these pollutants to the bloodstream where they are transported to other organs of the human body (Shi *et al*., 2016).

Majority of the studies have established standard covariate adjustment for total particulate matter mass in models of particulate components and adverse health outcomes (Krall *et al*., 2015). Health effects due to PM_{10} exposure are exhibited depending on the time of exposure hence chronic and immediate effects have been experienced and reported. The length of exposure and concentration of PM_{10} are important factors that influence health end points. Overall, acute exposures to high concentrations of aerosols are much less damaging than long-term exposure. The latter exposure to cement dust has been further associated with a higher prevalence of chronic respiratory symptoms, reduction of ventilatory capacity including development of silicosis and lung cancer (WHO, 2006).

Exposure to PM_{10} can result in premature death in people with pre-existing lung diseases. In addition, these exposures can cause non-fatal heart attacks and exacerbate asthma. Coarse particles are known irritants to the eyes, nose and throat of human beings. Atmospheric aerosols have a negative impact to the environment with PM_{10} being the main cause of reduced visibility in most

urban areas resulting in vehicular accidents. Aluminum dust and fumes, a component of cement dust exposure among workers have shown a rise in incidences of pulmonary fibrosis, which are dependent on the air fraction of dust; wheezing, dyspnea, or impaired lung function have also been associated with aluminum exposure (Ammar Awad Elshiekh *et al*., 2018).

A number of studies have indicated a strong correlation between elevated levels of PM_{10} and increased respirtory diseases. According to a survey conducted by the Kenya National Bureau of Statistics (KNBS) between 2009 and 2015, the respiratory diseases were observed to be on the rise.

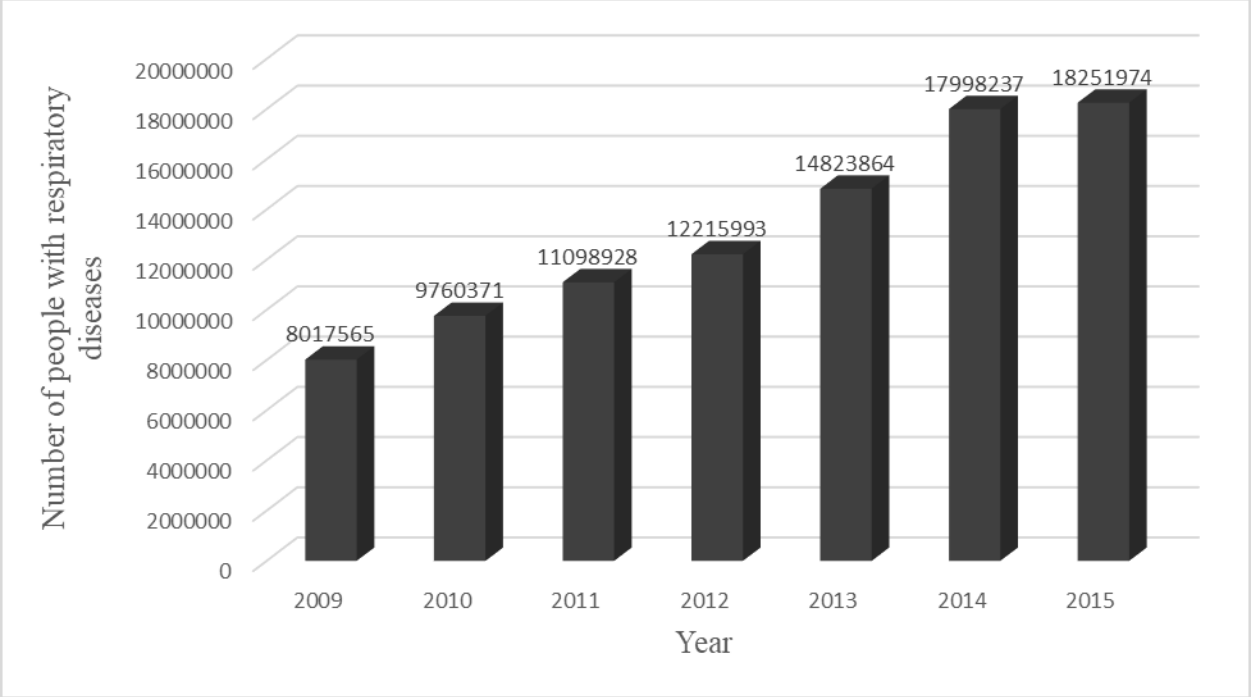

Figure 2.3: Kenyan population who had respiratory diseases in Kenya from 2009 to 2015

Source: KNBS, 2019.

2.2. Cement production in Athi River Municipality

Cement is a basic binding material in the building and construction industry. The industry is popular and profitable; however, it faces various challenges since it is not environmentally friendly in nature (Potgieter, 2012). In Kenya, there is a rising in the cement production to satisfy increased cement demand. Consequently, the number of cement industries has been on the rise in conjunction with the construction sector which has resulted in high levels of air pollution. Athi River Municipality in Kenya has six cement factories with production capacity of eight million tons per annum as shown in Table 2.1.

Table 2.1: Annual production capacities of cement companies in Athi River Municipality

Company	% Market share	Capacity in (million) tons
Bamburi	32.6	2.1
Mombasa cement	15.8	1.6
East Africa Portland cement	15.1	1.3
Savannah cement	15	1.0
National cement	8	1.0
Athi River Mining, Africa ltd	13.5	1.0
Total	100	8.0

Source: KNBS, 2019.

2.2.1: Cement manufacturing process

Cement is the main material used to produce concrete and mortar during the hardening of gravel and sand in concrete, meaning that their use in modern era is great. Cement manufacturing uses energy to process raw materials consisting of mainly limestone, clay, sand and iron ore for clinker

production. The clinker is then ground with gypsum and limestone to produce cement. Dry method of production is preferred as compared to wet method that consumes more energy. Wet method is an old technology where slurry is formed by grounding moist filled material with water, then pumping it directly to the kiln or slurry dryer. The wet method consumes more energy due to evaporation of additional water. In dry process, raw material is grounded and dried to raw mill and then fed to pre-calciner kiln making the method more energy saving. Four steps are used in cement manufacturing process as follows (Gaharwar *et al*., 2016).

2.2.1.1: Step 1 - Quarrying

Cement rock such as shale, clay and limestone are blasted and broken down into small rocks which are transported to a limestone crusher using tippers and dumpers. They are then crushed to between fifteen to twenty millimeters and taken through the cement manufacturing process.

2.2.1.2: Step 2 - Raw material preparation

The efficiency of this reaction is increased through grinding of the blasted rock into fine particles. A homogeneous blend is formed by thoroughly mixing the required chemical composition (the raw meal). Superior quality particles with size distribution are a necessary characteristic for calcination.

2.2.1.3: Step 3 – Clinkering

Raw materials used in the manufacturing of cement are dried and fed into rotating kiln. At high temperatures, the raw meal is thermally decomposed (for example by decomposing calcium carbonate at about 900 ^{0}C that produces carbon dioxide and calcium oxide) by the kiln to form

dicalcium silicate ($2CaO.SiO_2$), tricalcium silicate ($3CaO.SiO_2$), tricalcium aluminate ($3CaO.Al_2O_3$) and tetra calcium alumino-ferrate ($4CaO•Al_2O3•Fe_2O_3$). Clinker is then stored in silos after dropping it into rotary cooler where it is cooled under controlled conditions.

2.2.1.4: Step 4 - Cement milling

The clinker produced normally has the same characteristics as cement despite having particle size of up to 3 cm in diameter. It is typically converted to cement by grinding it into fine powder. Generally, cement is a fine powdery material consisting of a mixture of 19 -22 % of silica (SiO_2) ,62.7 % of calcium oxide (CaO), 2-5 % of ferrous oxide (Fe_2O_3), 4-8 % of alumina (Al_2O_3) and 1-2 % magnesium oxide (MgO) with also thallium and selenium forming other impurities. The cement production has several environmental effects such as emission of greenhouse gas including CO_2 and dust.

Almost all the production units of cement industries that include raw mill, kiln, coal mill, cement mill are point sources of pollutant generation and emission. Others include open air handling, loading and unloading of cement are fugitive sources of emission. The cement industries therefore generate continuous visible clouds of dusts which depending on the wind flow regime are transported and diluted, modified and ultimately removed through settling on the surrounding areas or washed out of the atmosphere during the rainy seasons. The dust is easily re-suspended when disturbed especially during the dry season. The whole process of cement production is therefore associated with considerable dust emission. These points sources of dust emission during cement manufacturing process are shown in Figure 2.4.

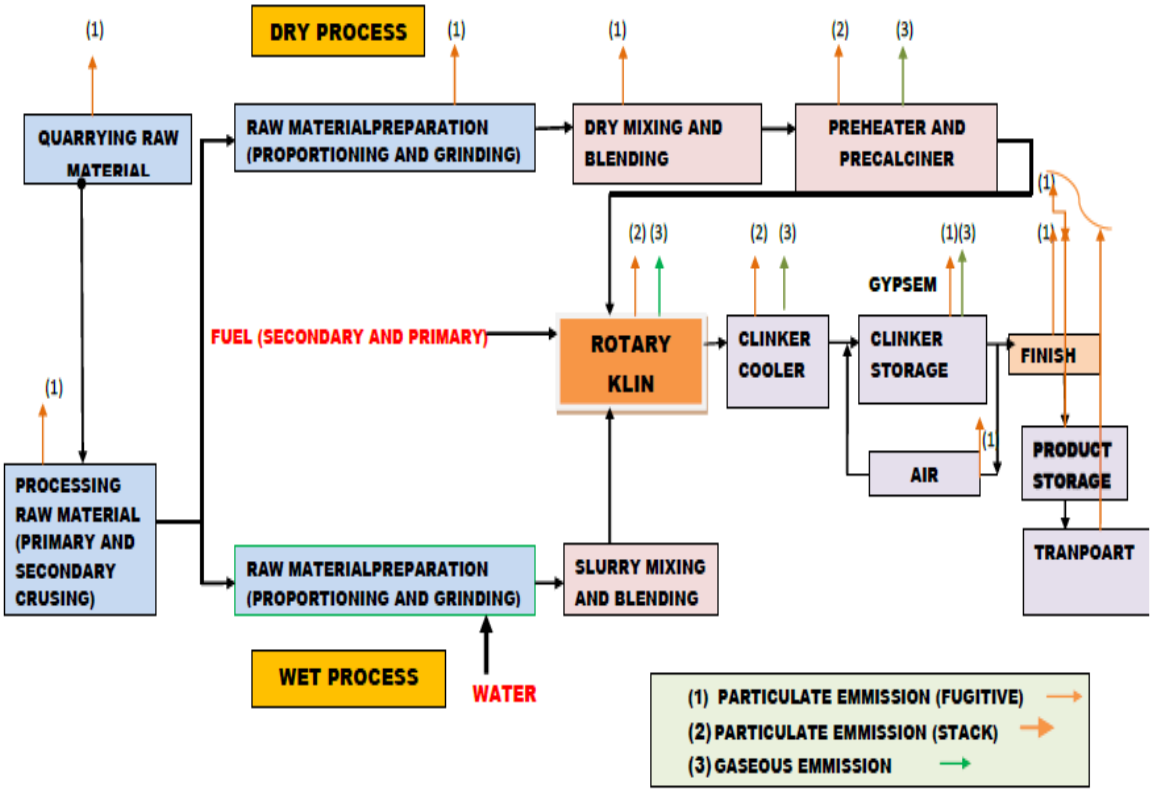

Figure 2.4: Point sources of emission during cement manufacturing process

Source: US EPA, 1998.

The cement manufacturing process is also associated with emission of different pollutants as shown in Table 2.2

Table 2.2: Air pollutants generated from Cement Manufacturing Process

Point of generation	Air pollutant
Coal Mill	Dust
Clinker	Dust, SO_2, VOC, NOx, CO_2, CO
Clinker Cooler	Dust
Cement Mills	Dust
Crusher Stack	Dust
Packing Plant Stack	Dust

Source: (Potgieter, 2012).

2.3: Emission control technologies in cement industries

The emission control involves collection and recycling of dust within the cement factories. This is necessary to reduce mass load emitted from stacks including fugitive emissions. Stack heights must therefore be appropriate, and the most efficient technique for particles removal should be applied. However, Were *et al* (2020) observed low stack heights that were inadequate in dispersing emissions in most industries in Athi River Municipality. Nevertheless, there are several emission control technologies that include: mechanical collectors or also known as dust cyclones or multi-cyclones, electrostatic precipitators, fabric filters and particulate scrubbers.

2.3.1: Mechanical collectors

Cyclone separator (Figure 2.5) is the most common inertial device which is usually a vessel cylinder bearing a tapering conical base. Entry to the cyclone body by the gas is commonly through the tangential and a helical spin by the gas steam imparted by the flow. The principle behind inertia device is that matter tends to move in a straight line. Most frequently used carrier gas is flue gas which has lower momentum than particles found in a gas steam. In the event of directional change for steam, the gas is able to turn while particles follow in their original path. When this occurs, it allows physical separation of carrier gas from solids. Sufficient time is therefore required for the settlement of particles from the gas steam as it travels through these devices hence low velocity is essential for this process and is easily achieved by enlarging the cross-section flow area (Gallaer and Schindeler, 1963).

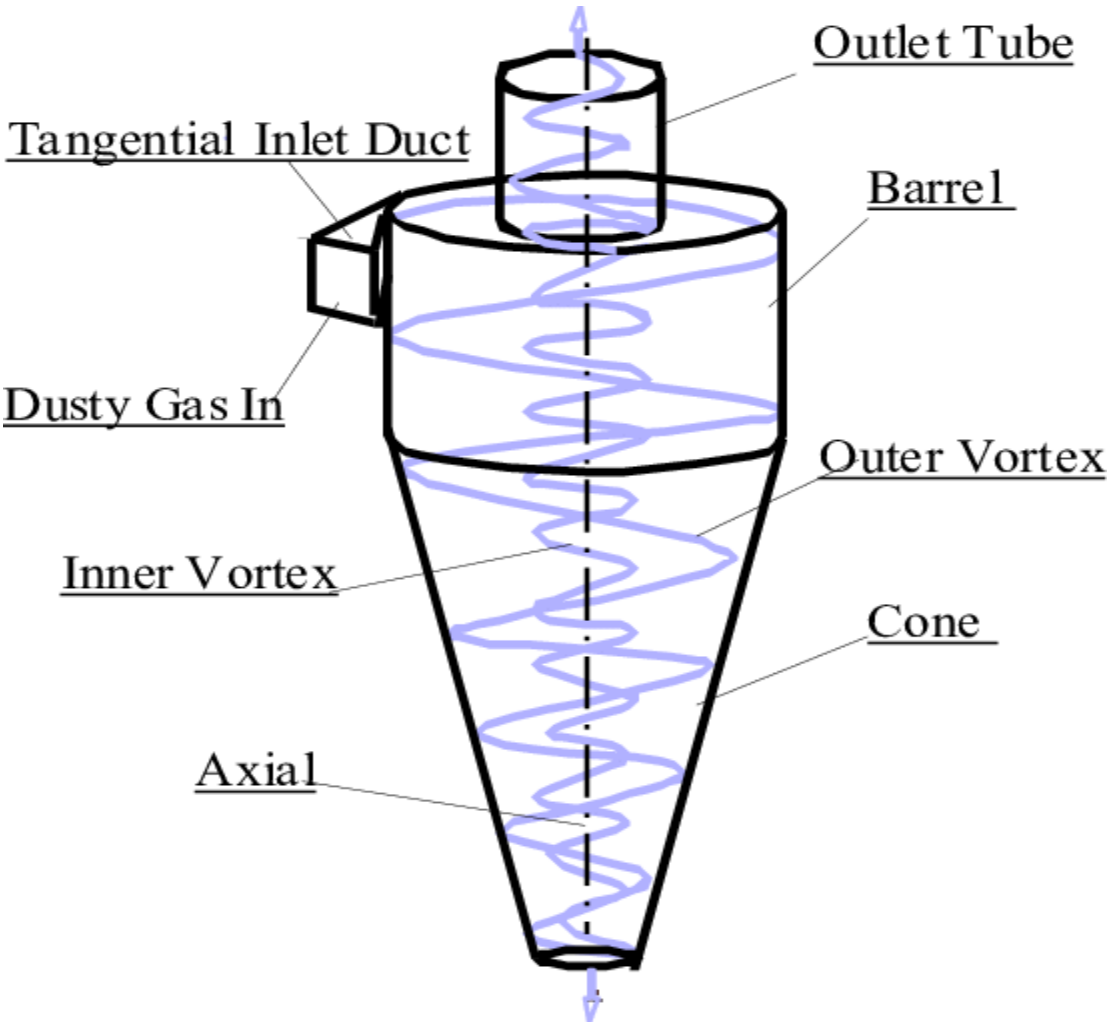

Figure 2.5: Schematic diagram of a cyclone

Source: (Gallaer and Schindeler, 1963).

2.3.2: Electrostatic precipitators

Electrostatic precipitators presented in Figure 2.6, function by using an oppositely charged electrode to draw dust particles imparted with electrostatic charge from a gas stream. Discharge electrodes emit ions that charge dust particles electrically via collision or diffusion. Collision ionizes particles with a diameter greater than a micron, while diffusion is applied to particles with less than one-micron in diameter. The charge obtained is then removed and the particles are retained for collection. The amount of dust collected, is dependent on the strength of electric field

within the ionization area, the surface area of particles and time consumed during charging (Wen *et al*., 2015).

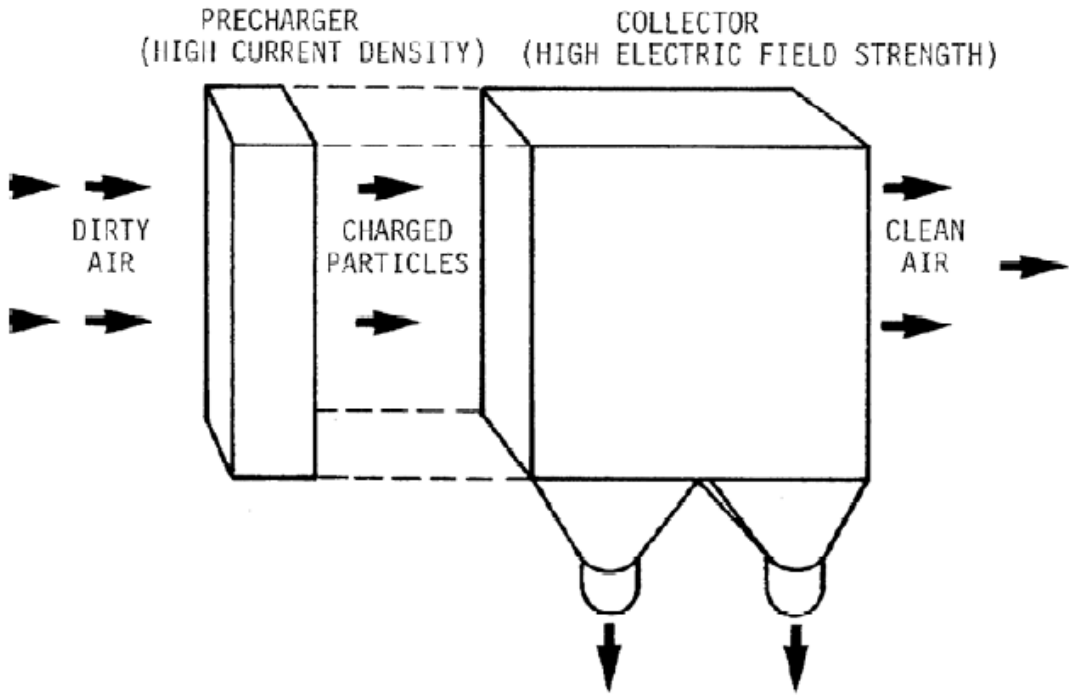

Figure 2.6: Schematic diagram of electrostatic precipitator

Source: (Wen *et al.*, 2015)

2.3.3: Fabric filters

Filter media found in bag filters range from woven fabrics, through synthetic materials that are needle-felted to glass cloths that are coated with Teflon. The media is used to control air pollution due to combustion through removal of particles (Figure 2.7). Filtration is the main process that occurs in the bag filters because a filter media is used to isolate solid materials from the gases. Sensitivity of these materials depends on dampness and temperature of prevailing environment (Bhargava, 2016a).

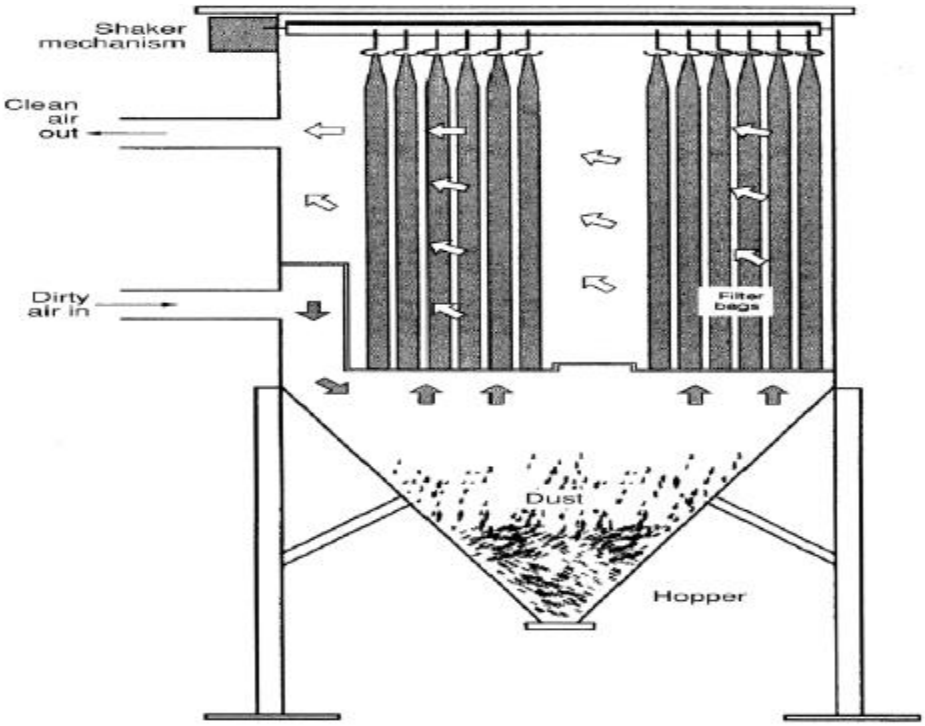

Figure 2.7: Schematic diagram of a bag filter

Source: (Bhargava, 2016a)

2.3.4: Particulate scrubbers

Particulate scrubbers shown in Figure 2.8 are for removal of soluble gaseous substances from gas streams which are in the form of packed towers. There is still wide usage of wet scrubbing as a method of air pollution control although its usage is slowly declining due to restrictions applied to waste waters disposal with inclusion of contaminated waters from the scrubbers. The basic principle underlying all scrubbing process is that it promotes contact between gaseous substances and liquid streams through high energy impaction to both gas and liquid streams. Another way is by provision of a large surface area on which occurrence of contact between the gas and liquid streams can be attained. Particle scrubbing are applied by three modes that include: impaction, interception and diffusion where a particle encounters a droplet of scrubbing liquor and the interactions leads to particle removal (Bhargava, 2016b).

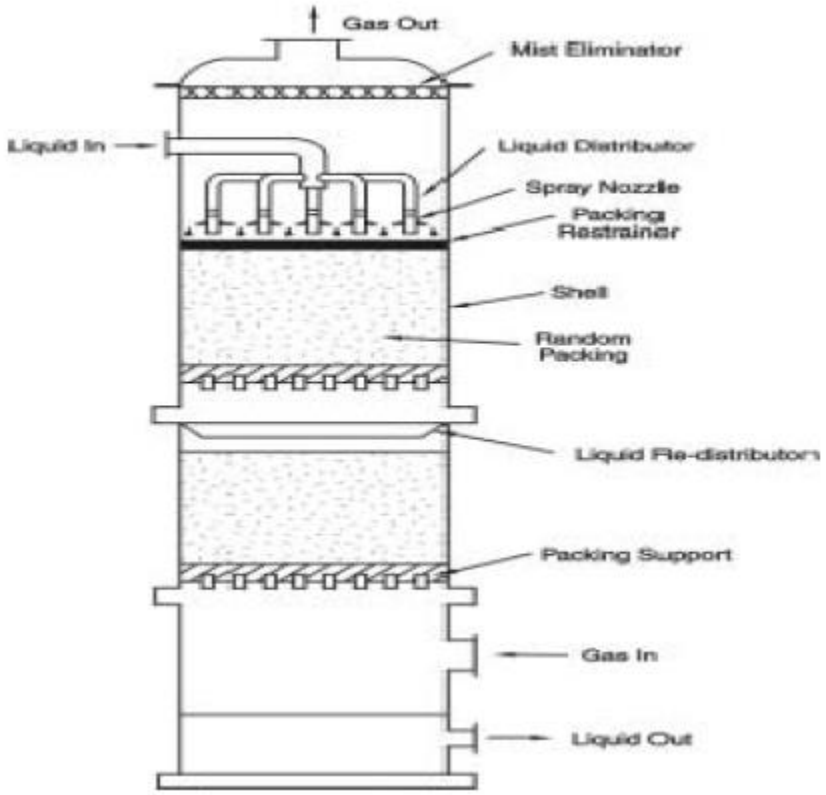

Figure 2.8: Schematic diagram of a wet scrubber

Source: (Bhargava, 2016b)

2.4. Air Quality Regulation in Kenya

Kenya has stipulated AQ regulations for industrial, residential and control areas by the National Environment Management Authority (NEMA) that ensures enforcement and compliance for various sites as shown in Table 2.3.

Table 2.3: Particulate matter and air quality limits

Particulate matter	Time average weighted	Sites		
		Industrial area (µg/m^3)	Residential, rural and other areas (µg/m^3)	Control area (ug/m^3)
Suspended particulate matter (SPM)	Annual average	360	140	70
	24 hrs.	500	200	100
Inhalable particulate matter (≤10 µm)	Annual average	70	50	50
	24 hrs.	150	100	75
Fine particles $PM_{2.5}$	Annual average	35		
	24 hrs.	75		

Source: NEMA, 2014

2.5: Meteorological factors affecting PM_{10}

Studies done on the relationship between PM_{10} and meteorological factors such as relative humidity, temperature, wind speed and wind direction have reported the latter influence on aerosol emission, transportation and deposition (Qin and Oduyemi, 2003). The aforementioned factors are important in affecting the AQ as they influence the concentration of PM_{10} in the atmosphere. Meteorology is also associated with cross border pathway pollution. Changes in weather and climate patterns have profound influence on the atmospheric pathways for long-range transport of gases and particles. The impact of rainfall on aerosol concentration is by removal of gaseous pollutants and deposition of PM_{10} through atmospheric chemical process (Islam, 2015). Air quality also changes with seasonal variation.

2.6: Method of analysis

PM_{10} is determined using techniques that measures either concentration or size distribution of atmospheric aerosols. Instruments utilizing gravimetric method are generally used with an advantage of carrying out chemical analyses. Gravimetric method requires accurate and precise weighing protocol for the results to be comparable. The technique is widely applied and most regulatory bodies including United States Environmental Protection Agency (US EPA) and European Union (EU) have adopted it. However, the gravimetric method determines average data for deployment period of the filter membrane. The technique has some limitation of high costs and manual process of operation although it is also useful when providing quick snapshot of PM_{10} at a site in order to determine locations for more intensive monitoring.

2.6.1: Air sampling

Air sampling of particulate matter has different approaches with marked advantages and disadvantages. The best method is dependent on availability of resources and equipment. For instance, grab sampling involves samples taken at a specific time and analyzed. More often, the samples are collected and taken to a different location for analysis. The disadvantage of grab sampling is that it is labor intensive. On the contrary, active sampling involves collection of samples frequently that can later be analyzed. This method can be automated but is very expensive. The third method is the application of sensors at a fixed position in the hazardous areas with a need for continuous data logging. With full time monitoring, sensors have excellent sensitivity, accuracy and rapid response time. Nevertheless, sensors need to be at fixed position and connected to the power supply.

Particulate air sampler offers a flexible platform for sampling of PM_{10}, $PM_{2.5}$ or TSP and sometimes for monitoring basic meteorological factors. These samplers can compute ambient pressure and temperatures which is detected via the sensors by constantly monitoring the 'mass flow rate'. The amount of air passing through the filter and the pump is important in estimating the volumetric flow rate. This is by the pump creating vacuum changes with a greater filter loading thereby bringing about more space. Constant sampling is therefore assured through integration of active volumetric flow control that moderates pump speed and air velocity. In addition, the power can be drawn from different sources, including the AC mains power adaptor, other options include battery pack or solar panel and battery combinations. Programmable time clock is usually incorporated that enables relative disposition of multiple time-based sampling programs. Figure 2.9 shows the instrumentation of air sampler inlet.

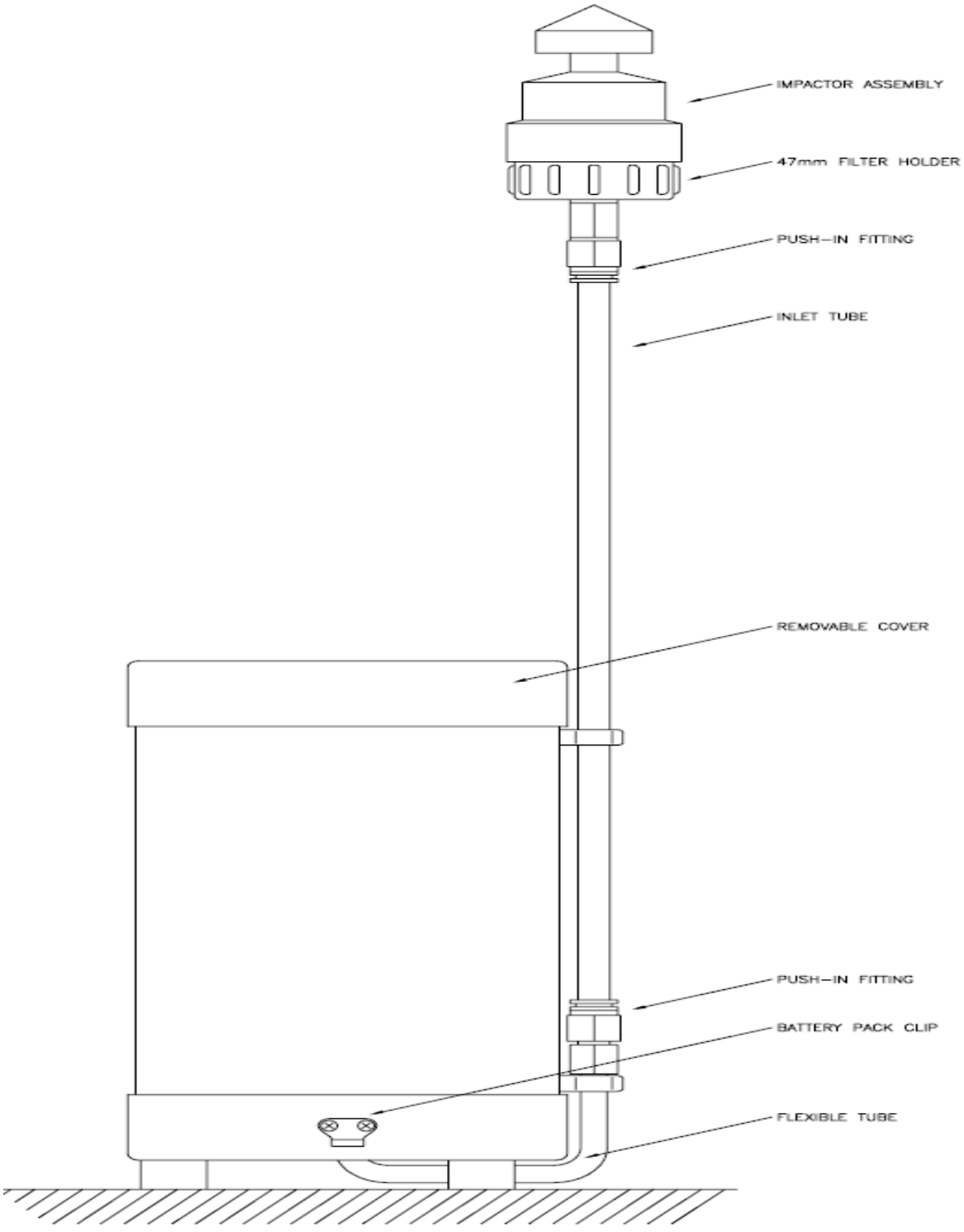

Figure 2.9: Air sampler Inlet Assembly

Source: Ecotech, 2021

2.6.2:X-ray fluorescence

X-ray fluorescence technique generally analyzes fluorescent rays in order to get elemental composition of a material. An energy dispersive x-ray fluorescence (ED-XRF) technology is used to determine the composition of PM_{10}. It is non-destructive method with minimal sample preparation in optimized conditions. It also consists of an excitation source for the sample, a detector, a sample chamber and an emission or fluorescence energy analyzer. Most XRF equipment are Menu-driven from a personal computer (PC). The instrumentation of EDXRF is shown in Figure 2.10.

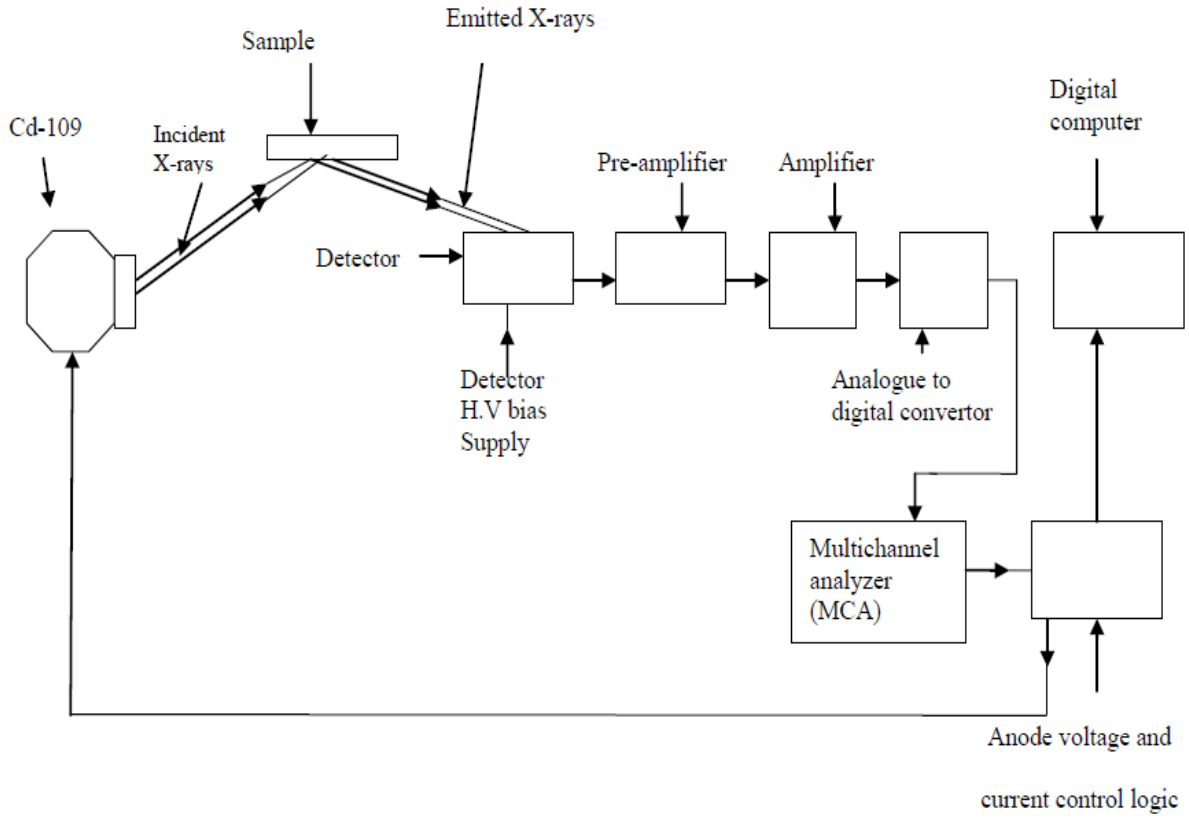

Figure 2.10: Instrumentation of Energy Dispersive X-ray Fluorescence

Source: Van Espen and Adams, 1981

CHAPTER THREE

MATERIALS AND METHODS

3.1: Introduction

The study was undertaken to determine the PM_{10} levels and meteorological factors that prevailed in the industrial, commercial and residential areas around the cement industries in Athi River Municipality, Machakos County. This was conducted during the rainy (April-June and October 2019) and dry (January-March and September 2019) seasons. Reconnaissance was subsequently established to map the sampling sites using Geographical Positioning System (GPS) and observations. The PM_{10} levels and elemental composition were determined using gravimetric technique and EDXRF, respectively.

3.2: Description of the study area

The study area, Athi River Sub-County in Machakos County, is geographically located at a latitude of 1.450^0 South (1^o 27'22.68" S) and longitude 36.98^0 East ($36^0$58'41.74" E) as shown in Figure 3.1. It lies at 1530 meters above sea level. The Sub-County covers an area of 827.2 km^2 with an estimated population of 322,499 according to KNBS (2019). It hosts Mavoko Municipal Council Headquarters. The area around Athi River Municipality is designated as an industrial zone registering a 10% industrial growth. It is heavily industrialized with six actively operating cement factories namely: Bamburi, Savanah, East Africa Portland Cement, Athi River Mining, Mombasa Cement and National Cement given in Figure 3.1, with a total annual production capacity of eight million tons of cement. Besides, there were other industries that operated in Athi River town that comprised steelworks, minerals enterprises, Fahari blocks limited that made cabro blocks, incineration, lead acid battery recycling, long haul transport and quarrying. The town has many

commercial activities characterized by unplanned settlements with many shops scattered over the area.

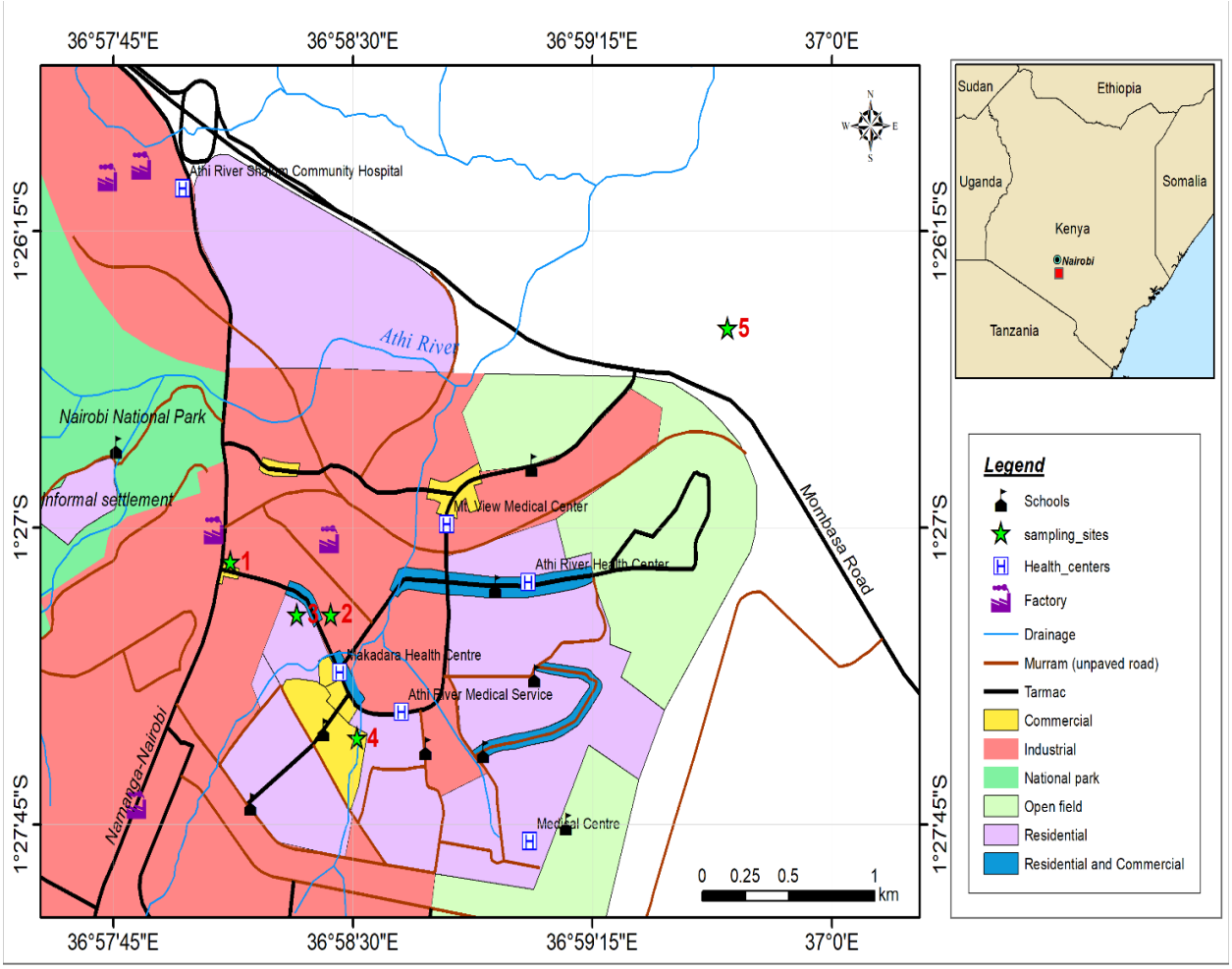

Figure 3.1: Map of Athi River showing sampling sites

Source: Department of Geology of the University of Nairobi, 2019.

The climate of this area was mild, and generally warm and temperate. Kenya is crossed by the equator; hence the climate is rather stable with minor seasonal changes (Figure 3.2). The municipality receives an annual rainfall of 599 mm, with two climatic seasons that include the wet and dry periods, with some variations within the month. The long and short rainy seasons are usually experienced between the months of February to May, and October to December,

respectively. These seasons were often followed by dry spells that were occasioned by strong winds. The annual temperature varied between 12.8 and 28.3℃ but was rarely below 10.0℃ or above 30.6℃. The predominant wind direction observed during the rainy season was East-South-Easterly (ESE) whereas during the dry season was East-North-Easterly (ENE). Wind speeds varied between 3.3 to 6.4 m/s during dry season and from 1.9 to 4.2 m/s during the rainy season.

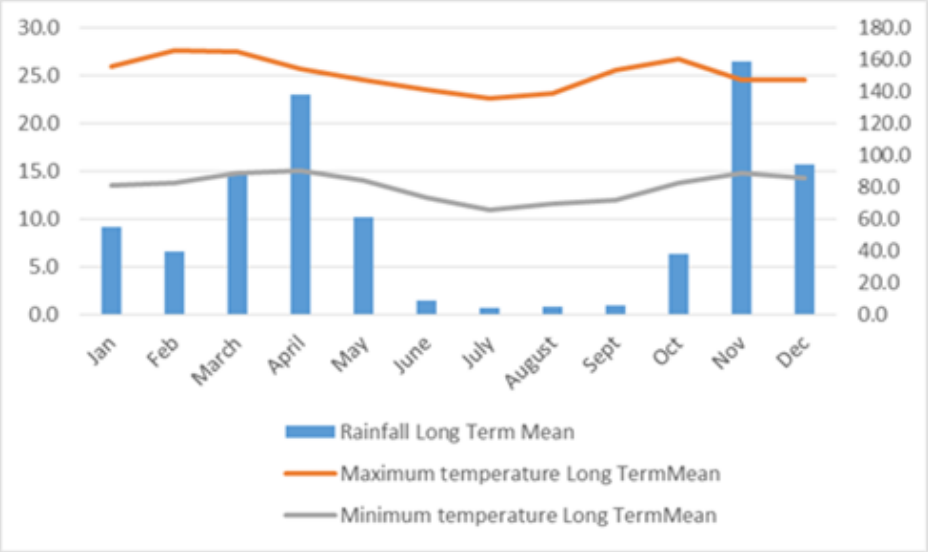

Figure 3.2: Variation in annual rainfall and temperature of Athi River Municipality

Source: Kenya Meteorological Department in Nairobi County (2019)

3.3: Sampling sites

Five sampling sites were purposively selected within the Athi River Municipality based on their proximity to the cement industries and free from any form of interferences and hence allowed free air circulation in the ambient atmosphere. The sampling sites included two industrial areas "A" and "B" denoted as Sites 1 and 2, two residential areas "A" and "B" represented as site 3 and 5 and one commercial area, denoted as site 4 (Figure 3.1).

3.4: Description of the sampling sites

The location of the sampling sites along with land use is presented in Figure 3.1. The description of sampling sites is as follows:

3.4.1: Industrial site "A"

This sampling site was adjacent to the high traffic density in Makadara Road Junction along Nairobi-Namanga Highway at a latitude (1^0 :27': 5.202'' S), longitude (36^0:58': 6.9888'' E) and altitude of 4967 ft. The site was sandwiched between two cement manufacturing factories. The Athi River Mining Cement factory was about five hundred meters North East of the site while the East Africa Portland Cement Company was approximately three hundred- and fifty-meters South West of the site. A car wash and other commercial activities were also in close proximity to these sites about forty meters.

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3.4.2: Industrial site "B"

The site was an open field at latitude (1^0 :27': 10.2564'' S), longitude (36^0:58': 25.8636'' E) and altitude of 4948 ft. It was also located about one hundred meters from the heavy traffic Makadara-Athi River road. The site was about one hundred and fifty meters from the Athi River Mining Cement Factory. Additional industries that were within its vicinity included, Minerals Enterprises Limited, Fahari Blocks Limited Cabro Manufacturers and Lead Acid Battery Manufacturing Industry.

3.4.3: Residential site "A"

The residential site "A" was located in non-industrial area about fifty meters from heavy traffic density along Makadara-Athi River road with a latitude of (1^0 :27': 13.1868'' S), longitude

(36^0:58': 19.496'' E) and altitude of 4967 ft. The main activity in the area was building and construction.

3.4.4: Commercial site

The site was in a commercial area located along Athi River road with a latitude of (1^0 :27': 26.4384'' S), longitude (36^0:58': 39.3132'' E) and altitude of 4954 ft. It was about one hundred meters from Steel Mill Manufacturing Industry, adjacent to a pitch and there was a heavy traffic along the Makadara-Athi River road.

3.4.5: Residential site "B"

The residential site denoted "B" was about one thousand meters off the heavy traffic Nairobi-Mombasa road and about one thousand two hundred meters from Steel Mill Manufacturing Industry with a latitude of (1^0 :26': 29.7384'' S) and longitude of (36^0:589': 40.3836'' E), and altitude of 4925 ft. This site ("B") was different from residential area "A" since it was located downwind of most of the industries like the Bamburi Cement Manufacturing Industry. As a result, site "B" experienced a direct effect of wind flow from these industries.

3.5: Sampling periods of particulate matter

The representative samples of PM_{10} levels were collected from five selected sites (two industrial, two residential and a commercial site) from Athi River municipality in Machakos County between January to March, and in September 2019 and between April to June, and in October 2019 during the dry and rainy seasons, respectively. The PM_{10} samples were collected for three hours, in the morning between 9.00 am and 12.00 noon and in the afternoon between 12.00 noon and 3.00 pm

for three consecutive days at each site during the dry season. The same procedure was followed during the rainy season to take care of seasonal variation of wet and dry deposition of the PM_{10}.

3.5.1: Collection and analysis of particulate matter

The PM_{10} levels were collected using air sampler (Model: Ecotec Microvolt-1100) with a nominal flowrate of 3 Liters per minute. The sampler was mounted at 1.5 m as an average approximate height of a breathing zone. It was equipped with size selective inlet for collection of PM_{10} concentrations that had an effective aerodynamic size of less than or equal to ten micrometers (10µm). PM_{10} was collected on a conditioned and pre-weighted polytetrafluoroethylene (PTFE) filter membrane with a 47 mm diameter, 0.2 µm pore size and support ring sequentially numbered. At the end of the programmed sampling period, the loaded filter membranes were removed from the sampling pump using forceps and stored in separate polyethylene petri-dishes. The loaded filter membranes were then re-conditioned in a temperature/humidity-controlled laboratory for 24-hours prior to re-weighing using unibloc shimadzu AUW220D analytical balance (Semi-micro balances) with a readability of 0.01mg (10 µg).

3.6: Determination of PM_{10} levels

The net weight of PM_{10} was determined by the difference in weight between the post-weight and pre-weight filter membranes and was reported in grams (g). The levels of PM_{10} were then determined following the two outlined steps 3.1 and 3.2:

Step 1: The total volume of air sampled was calculated using Equation (3.1)

$$V = Q\text{a} \times t \times 10^{-3} \qquad (3.1)$$

where:

V = volume (m^3) of air sampled for twenty-four hours

Qa = average flow rate (L/min)

t = total elapsed sampling time in minutes

10^{-3}=unit conversion factors for liters (L) into cubic meters (m^3)

Step 2: The PM_{10} levels were calculated in microgram per cubic meter ($\mu g/m^3$) of air using Equation (3.2).

$$PM_{10} = (Wf - W_I) \times 10^6/V \quad (3.2)$$

Where,

PM_{10} = concentration of PM_{10} in the ambient air in $\mu g/m^3$

10^6 = conversion factor from grams to micrograms

W_f = final weight of exposed filter in grams

W_I = initial weight of unexposed filter in grams

V = volume of air sampled in m^3

3.7: Determination of meteorological elements of the sampling sites

The meteorological data that encompassed relative humidity, rainfall, temperature, wind speed and wind direction were also monitored during morning and afternoon for three consecutive days at each of the sampling sites during the rainy and dry seasons using Mobile Apps-Meteoblue, 2019. The data sets were further acquired from the Kenya Meteorological Department under the Ministry of Environment and Forestry (Appendix 6) from the nearest fixed station, the Jomo Kenyatta International Airport. This data was subsequently augmented with those from Mobile Apps-Meteoblue for prevailing conditions during the entire sampling periods.

3.8: Determination of elemental composition of PM_{10}

Elemental composition of PM_{10} levels was determined on filter membranes using energy dispersive X-ray fluorescence (ED-XRF) (Model: Rigaku NEX CG ED-XRF) equipped with Rh X-ray tube source with Pd anode target, 50 W maximum power, 50 kV maximum voltage (Figure 3.3).

Figure 3.3: Rigaku NEX CG EDXRF spectrometer

Source: Rigaku, 2021

The Spectrometer was powered by RPF-SQX analytical software with qualitative and quantitative capabilities. By application of this software, semi-quantitative analysis of elements was done without necessarily having to do scrupulous quantitative analysis with standards. Heightened sensitivity, optimized peak/background ratio spectra were attained using up to three (Mo, Cu and RX9) secondary targets of which rather than having conventional direct excitation optics in a wide energy range (Abdullah *et al*., 2017). All samples were irradiated for 50 seconds to obtain characteristic radiation emitted by elements. A silicon drift detector embedded with high count rate capability and very good spectral resolution for data acquisition was used to collect the

fluorescent X-rays. The elemental composition was determined using in built RPF-SQX analysis software by applying fundamental parameter method, while accounting for the matrix effects.

3.9: Quality control and assurance

Quality Assurance/Quality Control (QA/QC) of the data was ascertained during sampling and analysis of PM_{10} in order to obtain reliable and accurate results. The QC procedures for the air sampling protocol involved maintenance and calibrations of equipment. Analysis of filter membranes was conducted according to gravimetric sampling method (ISO, 1989; MicroVol-1100 User manual 1.6, 2007). All analytical equipment used in this study were calibrated as per the manufacturer's guidelines. The equipment's included Ecotec microvolt-1100 air sampler, Rigaku NEX CG EDXRF and unibloc shimadzu AUW220D analytical balance (semi-micro balance) with a minimum display of 0.01mg. Field blank filters and filter membranes were stored in in a temperature (20.0^0C±1) and relative humidity (50%±5) controlled conditions in the Atmospheric Deposition Networks Laboratory, Department of Chemistry of the University of Nairobi for 24-hours prior to weighing and re-weighing. Reference filter membranes were also analyzed as appropriate to ensure the stability of the balance. All the filter membranes were weighed in triplicates and average weight taken when a variation of less than 5% was obtained (Were *et al*., 2020). The calibrated flow rate was also maintained at three liters per minute throughout the sampling period.

3.10: Data analysis

The results were analyzed using excel Statistical tool. The concentration of PM_{10} from the five sampling sites in the Athi River Municipality was reported in ug/m^3. The descriptive analysis that included the range and mean concentrations of PM_{10} and meteorological factors was carried out.

The variations in concentration of PM_{10} in different sampling sites and times of the day (morning and afternoon) was determined using student t-test or two-way Analysis of Variance (ANOVA) as applicable at a significance level of $p = 0.05$. The variables that influenced the concentrations of PM_{10} such as seasonal trends and meteorological factors (temperature, wind speed and relative humidity) were analyzed using Pearson correlation coefficient. Linear regressions analyses were also applied to estimate interrelationships at 5% of significance level. The elemental composition of PM_{10} was also evaluated and reported.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1: Introduction

The raw data of PM_{10} levels together with meteorological conditions that were obtained from the five sampling sites in Athi River Municipality in the morning and afternoon for three consecutive days at each site during the dry and rainy seasons are presented in Appendices 1-2. The statistical results are summarised in Tables 4.1-4.5 and Figures 4.1-4.8 and are further discussed.

4.2 Levels of PM_{10} in Athi River sites

The mean and range of PM_{10} levels in the sampled sites during the dry season are summarized in Table 4.1.

Table 4.1: Descriptive statistics of PM_{10} levels ($\mu g/m^3$) in selected sites (n=5) and comparison using t-test at p = 0.05 during morning and afternoon hours for 3 days at each site during the dry season.

Sampling Sites	Dry season (January- March and September 2019)				
	Morning (9.00 am – 12.00 noon)		Afternoon (12.00 noon – 3.00 pm)		P value at 0.05
	Mean ±SD ($\mu g/m^3$)	Range	Mean ±SD $\mu g/m^3$	Range	
Industrial "A"	592.6±133.5	481.5-740.7	271.6±46.6	222.2-314.8	0.0380
Industrial "B"	401.2±70.1	351.9-481.5	216.0±28.3	185.2-240.7	0.0407
Residential "A"	246.9±21.4	222.2-259.3	129.6±18.5	111.1-148.1	0.0034
Commercial	370.4±49.0	333.3-425.9	160.5±38.6	129.6-203.7	0.0034
Residential "B"	333.3±37.1	296.3-370.4	179.0±10.7	166.7-185.2	0.0110

The levels of PM_{10} greatly varied across the sites (n=5) and periods of the day (Table 4.1 and appendix 4). The industrial sites "A" and "B" had the uppermost levels of PM_{10} compared to the other sites during the dry season. This was regardless of the time of the day. Industrial site "A" had the highest mean level of 592.6±133.5 $\mu g/m^3$ in the range of 481.5-740.7 $\mu g/m^3$ during the morning hours and a mean level of 271.6±46.6 $\mu g/m^3$ that ranged from 222.2-314.8 $\mu g/m^3$ in the afternoon. The variations in the mean PM_{10} levels from industrial sites "A" and "B" could have been brought about by the differences in the location of these sites relative to cement industries and to some extent the road traffic emissions. This is because Industrial site "A" was sandwiched between the two cement manufacturing industries, the East Africa Portland Cement Company and the Athi River Mining whose processes were observed to emit dust thereby contributing to elevated levels of PM_{10}. The dense traffic involving heavy vehicles that transported raw materials and cement at Makadara road junction along the busy Athi River-Namanga highway could also have been a contributor to the PM_{10} levels that were reported. Several authors have further reported very high levels of PM_{10} in the industrial areas in the vicinity of cement industries and heavy traffic density road (Saheed Bada *et al*., 2013; Were *et al*., 2020).

Industrial site "B" had relatively lower mean levels of 401.2±70.1 $\mu g/m^3$ that ranged from 351.9-481.5 $\mu g/m^3$ in the morning hours and a mean of 216.0±28.3 $\mu g/m^3$ that ranged from 185.2-240.7 $\mu g/m^3$ in the afternoon compared to industrial site "A". This could be as a result of the industrial site "B" being located along Makadara-Athi River road that was not as busy as the main highway. The site was also adjacent to only one cement industry, the Athi River mining Cement Company as a main contributor of PM_{10} levels that were observed. Some other contributors could be emissions from nearby industries such as Minerals Enterprises Ltd and the lead acid battery

recycling company. Other studies have also reported significantly high levels of PM_{10} from industrial areas (Kim, 2014; Park and Ko, 2018).

The commercial site had mean levels of 370.4±49.0 μg/m^3 in the morning and 160.5±38.6 μg/m^3 in the afternoon which was lower than those of the industrial sites. The levels at the commercial site could be attributed to cement industries, vehicular emissions, the steel mill industry emissions and other commercial activities. The results were supported by those of Were *et al*. (2020) that revealed elevated PM_{10} levels in the schools located in the same commercial area.

Residential sites "A" and "B" had the lowest PM_{10} levels where "A" had 246.9±21.4 μg/m^3 in the morning and 129.6±18.5 μg/m^3 in the afternoon while site "B" had a mean level 333.3±37.1 and 179.0±10.7 μg/m^3, in the morning and afternoon, respectively. The PM_{10} levels reported in residential site "A" might have been caused by the unpaved roads and resuspension of particulates, building and construction that was ongoing and open combustion of waste which was a common practice in the area. Studies have shown that unpaved road emissions, construction activities and open burning of waste contribute to elevated PM_{10} levels (Were *et al*., 2020). The higher concentrations of PM_{10} in residential site "B" could be due to the unpaved roads, vehicular emissions from the busy Nairobi-Mombasa highway and the movement of particles by wind downwards since most of the companies were in the upwind direction. The results were not surprising as Casey *et al* (2017), also found high levels of PM_{10} in the sites located downwind of these industries.

Overall, the study showed high levels of PM_{10} that were significantly higher in the industrial sites, followed by commercial and residential areas respectively. Previous studies have also established

similar trends of higher PM_{10} levels in industrial sites, followed by commercial and residential areas (Mokola *et al*., 2019). Cement industries could have possibly contributed to the levels of PM_{10} in varying proportions that depended on the meteorological factors. These sites were also around the cement manufacturing industries that had strong influence to the levels of PM_{10} that were measured.

The levels of PM_{10} established, were significantly high ($P < 0.05$) during the morning hours compared to the afternoon periods. This was indicated by the p values that were less than 0.05 (0.0380, 0.0407, 0.0034, 0.0034 and 0.0110 for industrial sites "A" and "B", commercial and residential areas "A" and "B", respectively), suggesting that the differences were significant. The significant differences in the levels could have been due to the meteorological conditions that prevailed during the dry season that were varying across the sampling sites.

This study is in agreement with observations made by Mokola *et al.*, (2019) that revealed that the levels of PM_{10} were found to be significantly ($p < 0.05$) higher during the morning than the afternoon period. Culmination in levels observed during the morning period, could be associated with meteorological factors, especially atmospheric stability and wind speed which led to low rates of dispersion (Rahman *et al*., 2018). In addition, the PM_{10} levels were lower in the afternoon period as a result of possibly reduced traffic volumes causing lower emission rates. Dispersion conditions of the particulates in the morning was seemingly favored by increased mixing height (Bathmanabhan and Saragur Madanayak, 2010).

4.3: Influence of meteorological factors on PM_{10} levels during the dry season

The meteorological elements (Appendix 3) that included wind speed (m/s), wind direction, relative humidity (%) minimum and maximum temperature (^{0}C) that prevailed in the morning and afternoons across the sampling sites during dry season are summarized in Table 4.2.

Table 4.2: Meteorological conditions that prevailed across the selected sites (n =5) in the morning and afternoon periods during the dry season

Sampling site	Meteorological factors							
	Morning (9.00 am – 12.00 noon)				Afternoon (12.00 noon – 3.00 pm)			
	Wind speed Range(m/s)	Relative humidity Range (%)	Temperature Range (0C)	Wind direction	Wind speed Range (m/s)	Relative humidity (%)	Temperature Range (0C)	Wind direction
Industrial "A"	3.3-4.4	61-73	21-24	E, NE, ENE	4.4-5.3	43-64	25-29	E, ENE
Industrial "B"	5.0-5.6	45-57	22-24	NE, ENE	5.8-6.4	36-44	23-28	ENE, NE
Residential "A"	3.9-5.3	45-52	21-24	NE, ENE	4.7-5.6	36-46	23-29	E, ENE
Commercial	3.9-5.3	48-52	21-24	NE, ENE	5.8-6.4	31-44	23-28	ENE, NE
Residential "B"	3.9-5.6	53-56	22-24	NE	5.3-6.4	36-41	24-29	ENE

Note: NE, ENE means prominent winds were mainly North Easterly and East North Easterly while E, ENE implies that the prominent winds were Easterly and East North Easterly.

The Pearson's correlation coefficient was determined by regressing the values of PM_{10} and meteorological elements given in Appendix 3. Each of the meteorological factors given in Table 4.2 had a great influence on the levels of PM_{10} that were sampled from different sites (n=5).

4.3.1: Effects of wind speed

From Table 4.2 the wind speed varied from 3.3-5.6 m/s in the morning hours and 4.4-6.4 m/s in the afternoon hours across the sampling sites, with the afternoon periods experiencing high wind speeds. Pearson's correlation coefficient of wind speed with respect to the values of PM_{10} showed a moderately high negative correlation of R= -0.752. The regression value of PM_{10} obtained was r^2 = 0.565 (Figure 4.1). This implies that the strong winds had a negative influence on levels of PM_{10}, with high levels being prevalent in the morning than in the afternoon in all the sampled sites.

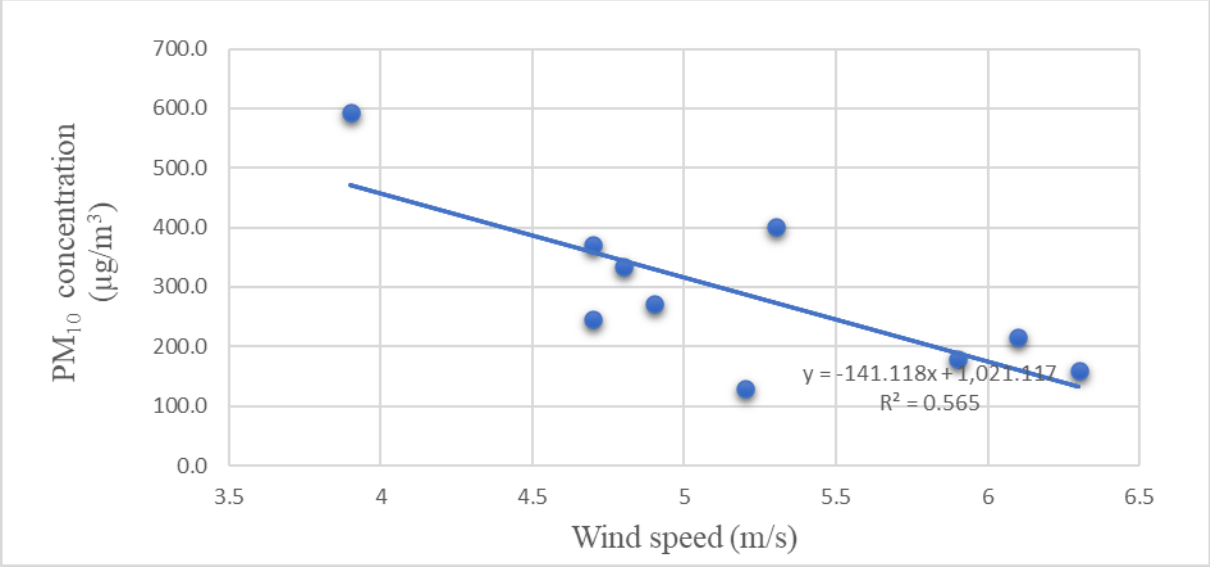


Figure 4.1: Correlation of PM_{10} levels and wind speed (m/s) during the dry season.

The strong winds that generally prevailed in the afternoons across the sampling sites dispersed PM_{10} over a large area. On the contrary, moderate winds that were observed mainly in the mornings across the sites allowed air to mix leading to a buildup of PM_{10} levels. As a result of the stable environment and long residence time of PM_{10} in the air, comparatively high levels of PM_{10} were reported in all the sites during the morning hours compared to the afternoon hours. This may also explain the elevated levels of PM_{10} that were observed in the industrial site "A" that had moderate

wind speed between 3.3 and 4.4 m/s in the morning, and from 4.4 to 5.3 m/s in the afternoon. To a larger extent the industrial site "B" had lower PM_{10} levels and stronger wind speeds that varied from 5.0-5.6 m/s in the morning and 5.8-6.4 m/s in the afternoon. In addition, the stronger winds that measured in the industrial site "B" could be responsible for the greatest variation observed as evidenced by the highest standard deviation (592.6±133.5) of 133.5 from the mean when compared to the smallest (179.0±10.7) of 10.7 reported from the other sampled site. Several studies are in agreement that wind speeds can blow PM to a certain geographical area and have tendencies of dispersing and diluting them thereby lowering their concentrations (Ayanlade and Oyegbade, 2016). An increase in wind speed has also been found to significantly contribute to a decline in the levels of PM_{10} and had influence on the elemental composition (Radzka, 2020).

4.3.2: Effects of relative humidity

From Table 4.2, the percentage (%) relative humidity (RH) across the sampling sites ranged from 45-73 % in the morning and 36-64 % in the afternoon hours during the dry season. The RH was slightly lower in the afternoon which could be attributed to the increased evaporation due to increased temperature that was reported in the afternoon. Pearson's correlation coefficient was applied on the RH with respect to the concentration of PM_{10} and had a high positive correlation of $R = 0.906$ and the regression value of PM_{10} was $r^2 = 0.820$ (Figure 4.2).

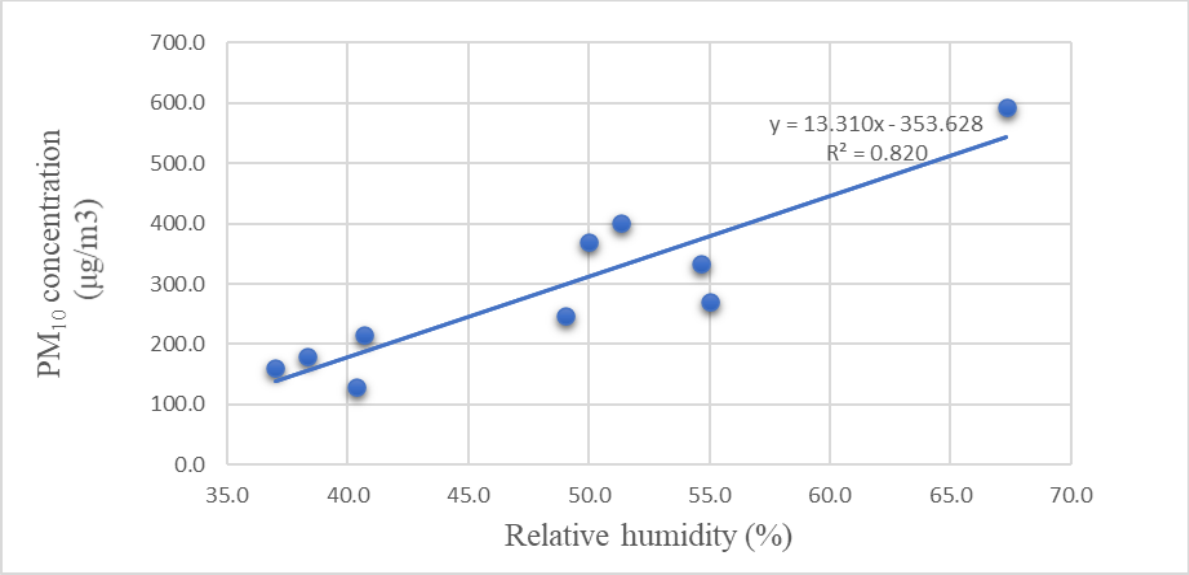


Figure 4.2: Correlation of PM_{10} levels and relative humidity (%) during the dry season

The highest PM_{10} concentration was observed during the morning period and the lowest was in the afternoon. This can be largely attributed to dry deposition of PM_{10} levels. It was observed that RH influenced PM_{10} to gather mass and ultimately settle on the ground rather than becoming airborne (Kayes *et al*.,2019). In addition, it is apparent from Table 4.2 that the industrial site "A" experienced the highest RH in both morning (61-73%) and afternoon (43-64 %) periods and had the highest levels of PM_{10} that ranged from of 481.5-740.7 µg/m^3 and 222.2-314.8 µg/m^3, respectively when compared to the other sampling sites.

4.3.3: Effects of temperature

Table 4.2 presents temperatures ranging from 21-24 ^{0}C in the morning period and 24-29 ^{0}C in the afternoon during the dry season. The Pearson's correlation coefficient was performed on temperature in relation to PM_{10} levels and showed a moderately high negative correlation of R= -0.783 and the regression (r^2) value of 0.613 was obtained (Figure 4.3). The negative correlation explains clearly why the levels of PM_{10} were significantly ($p < 0.05$) higher in the mornings when

the temperatures were relatively low than in the afternoons. Similar negative correlations between PM_{10} and temperature were reported by Giri *et al.*, (2008) who also revealed that PM_{10} was mainly from soil or road dusts and absorbed water vapors from the atmosphere and was easily deposited to the ground.

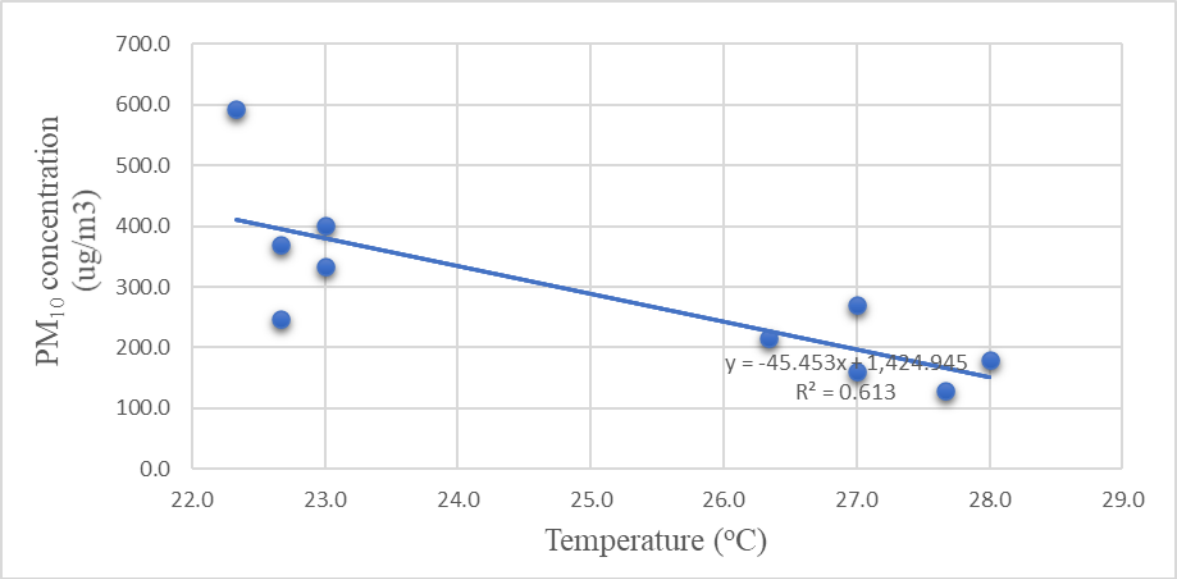


Figure 4.3: Correlation of PM_{10} levels and the temperature (^{0}C) during the dry season

4.3.4: Effects of wind direction

The predominant wind direction varied from NE-ENE in the morning to E-ENE in the afternoon period across the sampling sites (Table 4.2). This study found the major winds were impacting on PM_{10} levels in the residential site ‘’B” that was situated downwind of most the cement manufacturing industries. The site had a mean PM_{10} level of 333.3±37.1 µg/m^3 in the morning hours and 179.0±10.7 µg/m^3 in the afternoon in comparison to residential ‘’A’’ that was upwind and a lower mean level of 246.9±21.4 µg/m^3 in morning and 129.6±18.5 µg/m^3 in the afternoon hours. This suggests that wind direction controlled the path that PM_{10} followed and therefore a

correlation between the two existed (Radzka, 2020). Several studies have made similar conclusion when examining the relationship between PM_{10} levels and wind direction while investigating predominant winds (Lee and Kim, 2018; Lee *et al*., 2011).

4.4: Levels of PM_{10} in Athi River sites during the rainy season

The mean±SD and range (μg/m^3) of PM_{10} levels during the rainy seasons for morning and afternoon hours is given in Tables 4.3.

Table 4.3: Descriptive statistics of PM_{10} levels (μg/m^3) in selected sites (n=5) and comparison using t-test at p = 0.05 during morning and afternoon hours for 3 days at each site of the rainy season

Sampling Site	Rainy season (April- June and October 2019)				p value at 0.05
	Morning (9.00 am-12.00 noon)		Afternoon (12.00 noon-3.00 pm)		
	Mean ±SD μg/m^3	Range	Mean ±SD μg/m^3	Range	
Industrial "A"	302.5±56.6	240.7-351.9	166.7±37.1	129.6-203.7	0.0082
Industrial "B"	277.8±32.1	259.3-314.8	154.3±28.3	129.6-185.2	0.0025
Residential "A"	111.1±18.5	92.6-129.6	43.2±10.7	37.0-55.6	0.0081
Commercial	246.9±46.6	203.7-296.3	86.4±21.4	74.1-111.1	0.0102
Residential "B"	197.5±38.5	166.7-240.7	74.1±18.5	55.6-92.6	0.0098

From Table 4.3 and appendix 5, comparable trends were observed in the levels of PM_{10} across different sampled sites during the rainy season as those of the dry season (Table 4.1) suggesting that PM_{10} levels were from a common source. The industrial areas had also the highest levels of PM_{10} compared to the other sampled sites. The industrial site "A" had a high mean level of 302.5±56.6 μg/m^3 in the morning and mean level of 166.7±37.1 μg/m^3 in the afternoon while industrial area "B "had a mean level 277.8±32.1 μg/m^3 and 154.3±28.3 μg/m^3, respectively. This was followed by the commercial site with a mean level of 246.9±46.6 μg/m^3 in the morning and 86.4±21.4 μg/m^3 in the afternoon the lowest were from the residential areas of site "A" with a mean level of 111.1±18.5 μg/m^3 in the morning and 43.2±10.7 μg/m^3 in the afternoon and "B" with a mean level of 197.5±38.5 μg/m^3 in the morning and 74.1±18.5 μg/m^3. It is therefore clear from these views that PM_{10} levels were high in the industrial areas, followed by the commercial site then residential areas in the vicinity of the cement industries irrespective of the period of the day. This indicates that having cement manufacturing plant in industrial areas is associated with substantial levels of PM_{10}.

The levels of PM_{10} were also observed to be significantly high ($P < 0.05$) during the morning compared to the afternoon periods in all the sampled sites. This is demonstrated by p values that were less than 0.05 when student t-test was performed. The p values were 0.0082, 0.0025, 0.0102, 0.0081 and 0.0098 in the industrial site "A" and "B", commercial site and both residential sites "A" and "B", respectively. The significant differences in the levels could also be attributed to the varying meteorological conditions across the sampling sites (Table 4.4).

4.5: Influence of meteorological factors on PM_{10} levels during the rainy season

The same meteorological factors that influenced PM_{10} levels during the dry season were also investigated during the rainy season (Table 4.4).

Table 4.4: Meteorological conditions that prevailed across the sampling sites in the morning and afternoon periods during the rainy season

Sampling site	Meteorological factors							
	Morning (9.00 am – 12.00 noon				Afternoon (12.00 noon – 3.00 pm)			
	Wind speed Range(m/s)	Relative humidity Range (%)	Temperature Range (0C)	Wind direction	Wind speed Range (m/s)	Relative humidity Range (%)	Temperature Rang(0C) e	Wind direction
Industrial "A"	2.2-3.6	65-88	16-20	S, ESE	3.1-4.2	61-77	20-22	E, ESE
Industrial "B"	2.2-3.3	71-77	19-21	SE, SSE	3.1-3.9	56-74	20-23	ESE, SSE
Residential "A"	2.2-2.8	55-81	17-20	ESE, E	3.1-3.3	48-70	19-24	E, ESE
Commercial	2.5-3.1	62-80	16-20	ESE, SSE	3.1-3.9	60-76	18-23	E, ESE
Residential "B"	1.9-3.1	71-77	15-20	S, SSE	2.5-3.6	66-70	18-22	SE, SSE

Note: E, ESE means prominent winds were mainly East and East South Easterly while SE, SSE implies that the prominent winds were South Easterly and South-South Easterly

The influence of the meteorological conditions that included wind speed, relative humidity, temperature and wind direction which prevailed in different sampling periods during the rainy

season were evaluated with the PM_{10} values (Appendix 3) using Pearson's correlation and regression presented in Figures 4.4-4.6.

4.5.1: Effects of wind speed

From Table 4.4, the wind speed ranged from 1.9-3.6 m/s in the morning and 2.5-4.2 m/s in the afternoon hours. Pearson's correlation coefficient of wind speed with respect to the concentration of PM_{10} showed a low negative correlation of R= -0.374. The regression value of PM_{10} was r^2 = 0.140 as shown in Figure 4.4. This implies that the strong winds had a slight negative influence on levels of PM_{10} that was reported, with relatively high levels of PM_{10} being prevalent in the morning than in the afternoon in all the sampling sites.

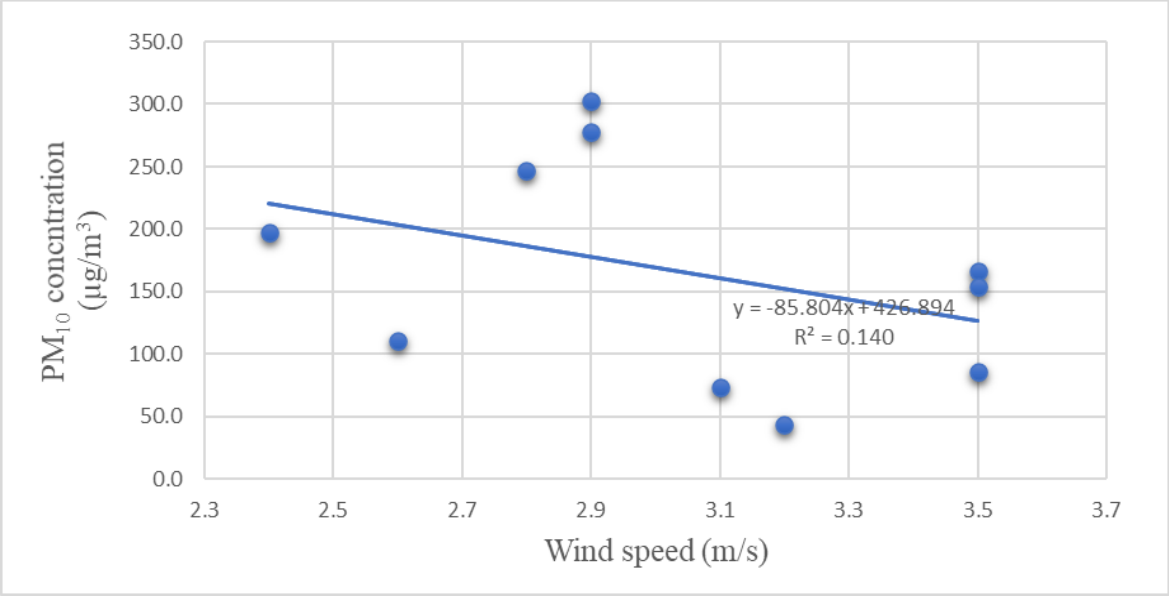


Figure 4.4: Correlation of PM_{10} levels and wind speed (m/s) during the rainy season

The relatively strong winds that were generally observed in the afternoons blew the PM_{10} to a greater extent whereas moderate winds that were mainly in the mornings across the sampling sites

permitted air to mixing resulting in an accumulation of PM_{10} levels. A stable environment and long residence time of PM_{10} levels resulted in high levels of PM_{10} in all the sampling sites during the morning hours compared to the afternoon hours. In the mornings a cold pool of air close to the surface may have separated the slow-moving surface air from the high-speed winds above. During the afternoon period, the air got warm and may have been forced to mix vertically, high-momentum air was mixed downward and the vertical wind speed profile evened out. In addition, low wind speeds could not disperse the PM_{10} causing higher levels as was apparent in the morning period in all the sites (Cichowicz *et al*., 2020).

4.5.2: Effects of relative humidity

The RH (%) across the sampling sites ranged from 55-88% in the morning and 48-77% in the afternoon hours (Table 4.4). In the afternoon, the RH was slightly lower which could probably be due to increased evaporation as a result of increased temperatures that were observed in the afternoon. Pearson's correlation coefficient was applied on the RH with respect to the concentration of PM_{10} had a high positive correlation of R = 0.826 was obtained. The regression value of PM_{10} was $r^2 = 0.682$ as presented in Figure 4.5. This implies that wet deposition process was responsible for the low value of PM_{10} during the rainy season, where PM_{10} was removed from the atmosphere. This may have been the case due to the increased RH that accolated the rate of PM_{10} absorption in the ambient atmosphere. Rain droplets could have acted as natural scrubber during rainy season and hence reduced the PM_{10} levels in the ambient air (Bathmanabhan and Saragur Madanayak, 2010).

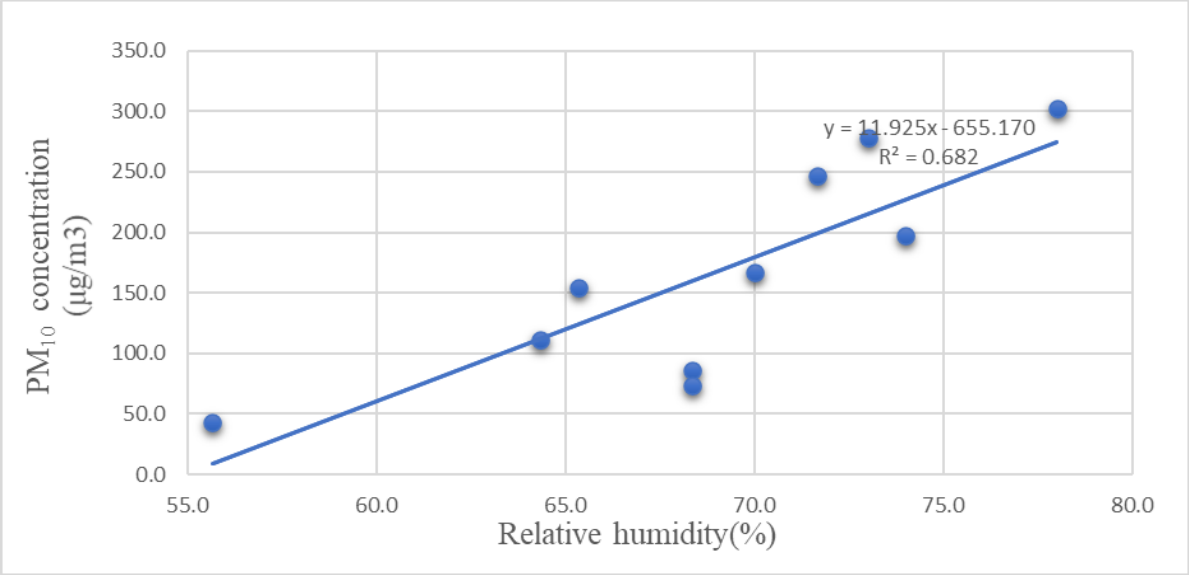


Figure 4.5: Correlation of PM_{10} levels and relative humidity (%) during the rainy season

The highest PM_{10} concentration was observed during the morning period and the lowest was in the afternoon. This can be largely attributed to dry deposition of PM_{10} levels to the ground. It has been observed that relative humidity influences PM_{10} to gather mass and ultimately settle on the ground rather than becoming airborne. With the increase in RH, PM_{10} therefore gathers mass and their levels increase (Giri *et al*., 2008). Table 4.4 showed that industrial site "A" experienced the highest RH % in both morning (65-88%) and afternoon (61-77 %) periods and had the highest PM_{10} mean levels of 302.5±56.6 and 166.7±37.1 µg/m^3, respectively as compared to the other sampling sites. However due to higher RH, PM_{10} levels were lower during the rainy than dry season as reported by Giri et al. (2008) in their study. The positive correlation between PM_{10} concentration and RH concurs with a study done by Kim (2019).

4.5.3: Effects of temperature

From Table 4.4, the temperatures ranged from 15-21^{o}C in the morning and 19-24^{o}C in the afternoon period. The Pearson's correlation coefficient was performed on temperature in relation

to PM_{10} levels and it showed a moderate negative correlation of R= -0.506 with a regression value of PM_{10} was r^2 = 0.256 as presented in Figure 4.6. This explains clearly why the levels of PM_{10} were higher in the in the morning when the temperatures were low as compared to the afternoon. Giri et al. (2008) discussed that PM_{10} composed of mainly soil or road dusts absorbed water vapors from atmosphere and was easily deposited to the ground and a similar negative correlation between temperature and PM_{10} levels was observed.

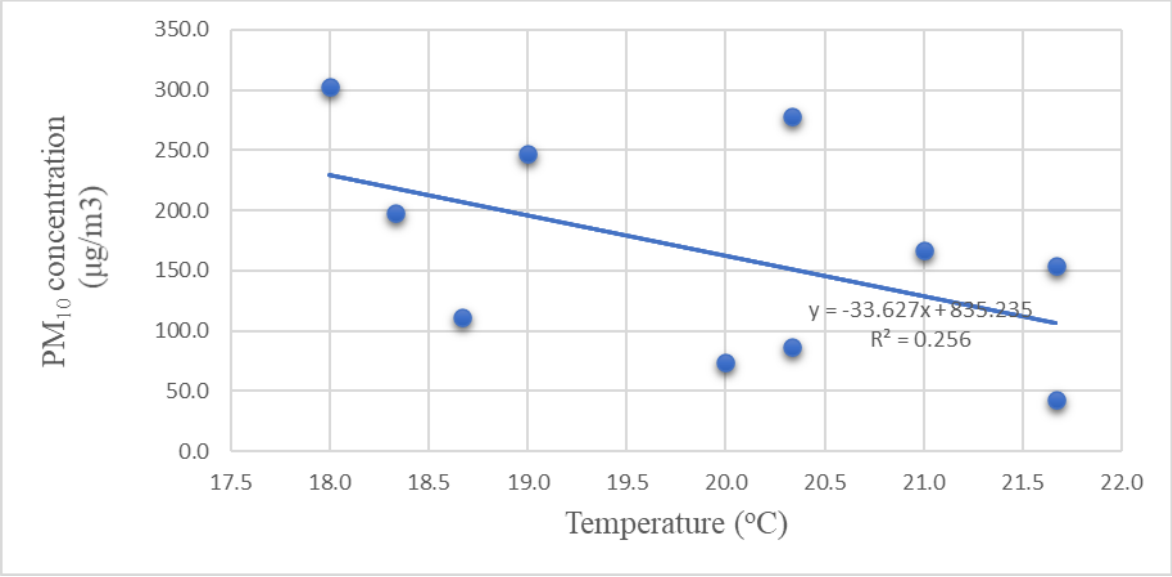


Figure 4.6: Correlation of PM_{10} levels and the temperature (^{0}C) during the rainy season

4.5.4: Effects of wind direction

The wind direction (Table 4.4) was dominantly ESE-SSE in morning and E-ESE during the afternoon hours, in the same way like during the dry season. The prevailing winds impacting PM_{10} levels for residential site ''B" situated downwind of most industries had a mean PM_{10} level of 197.5±38.5 µg/m^3 in the morning and 74.1±18.5 µg/m^3 in the afternoon. This was in contrast to the residential site ''A'' that was upwind of fewer industries and had a mean level of 111.1±18.5 µg/m^3 in morning and 43.2±10.7 µg/m^3 in the afternoon. The wind direction therefore controls the

distribution and dispersal of PM_{10} levels and hence there is a correlation (Radzka, 2020). Several studies are in agreement after investigation of the relationship between PM_{10} levels and wind direction while considering the predominant winds (Lee and Kim, 2018; Lee *et al*., 2011, Were *et al.*, 2020).

4.6: Comparison of PM_{10} concentrations during the dry and rainy seasons

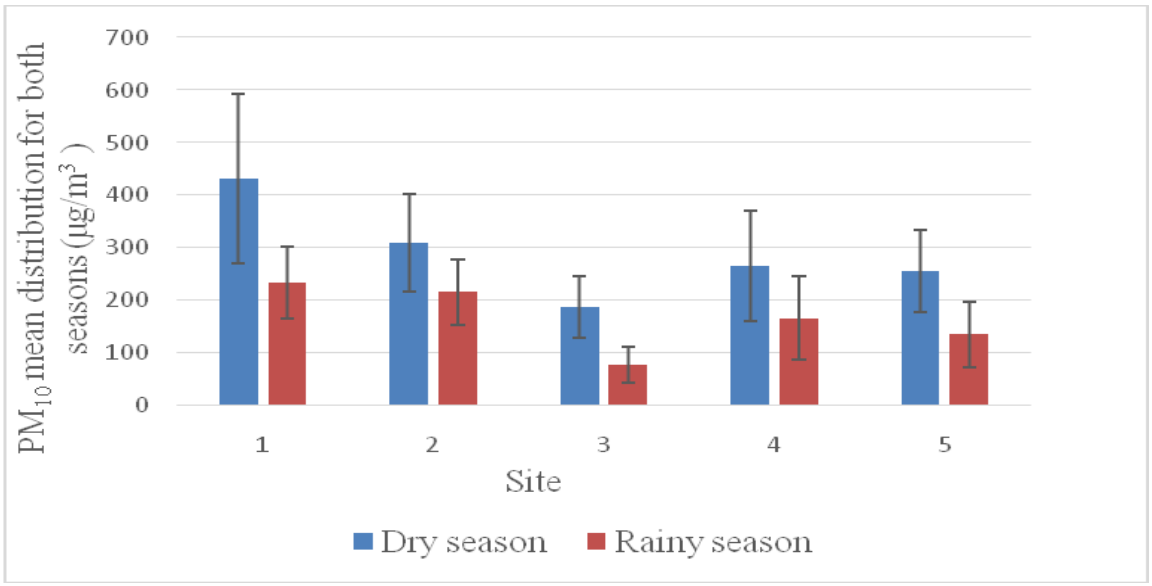
The mean levels of PM_{10} from Tables 4.1 and 4.3 were compared from each sampled site during the dry and rainy seasons using the student t-test at $p = 0.05$ (Table 4.5) and the corresponding Figure 4.7 was obtained. All the PM_{10} mean levels from the sampled sites were higher during the dry than the rainy season. The difference ($p < 0.05$) was significant as evidenced by all the p values obtained in Table 4.5 were less than 0.05 across the sampled sites.

Table 4.5: Descriptive statistics of PM_{10} mean distribution and comparison using t-test at p=0.05 in selected sites during dry and rainy season

Sampled Site	Mean distribution		P value at 0.05
	Dry season	Rainy season	
Industrial "A"	432.1	234.6	0.0096
Industrial "B"	308.6	216.0	0.0041
Residential "A"	188.3	77.2	0.0011
Commercial	265.4	166.7	0.0009
Residential "B"	256.2	135.8	0.0001

It should be noted that despite similar trends reported between the levels of PM_{10} with the highest concentrations in the industrial areas, followed by commercial area and least was from the

residential sites during the dry and rainy seasons, the levels were however significantly ($p<0.05$) lower in all the sampled sites during the rainy season (Figure 4.7).



Note sites: 1-Industrial "A", 2-Industrial "B", 3- Residential " A" , 4- commercial and 5-Residential "B" and the Error bars represent standard error

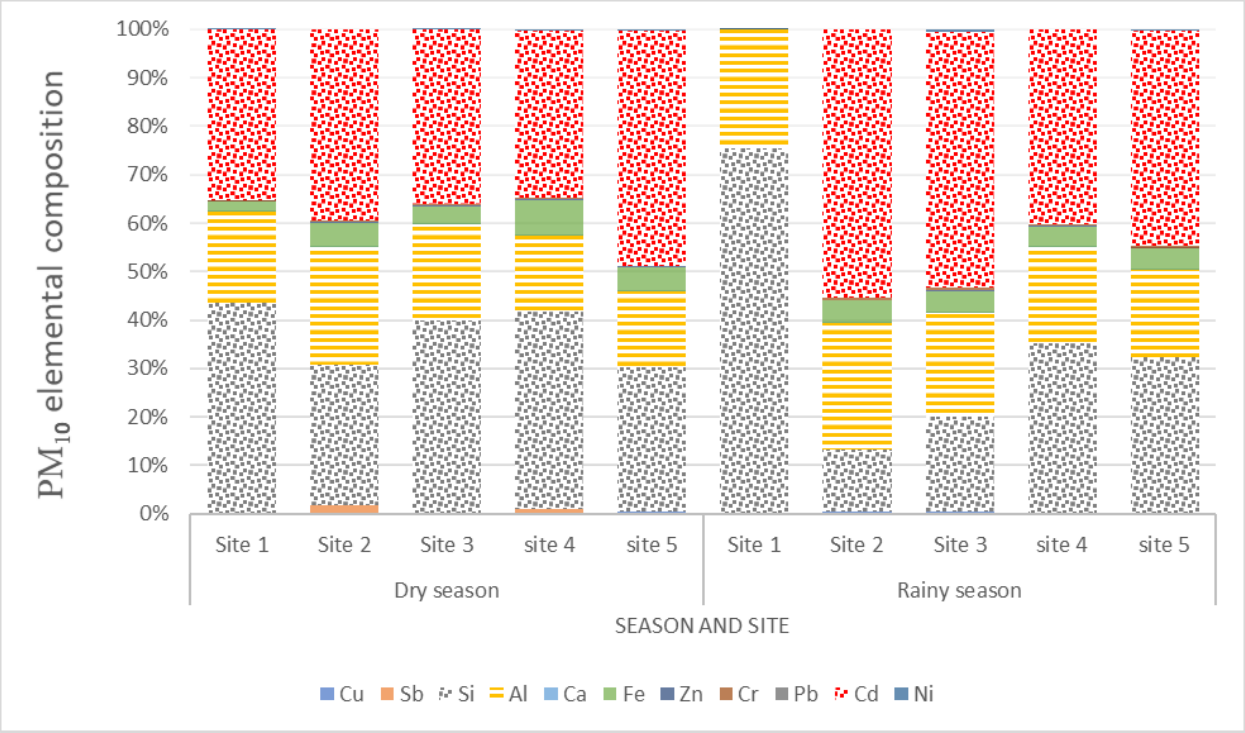
Figure 4.7: Comparison of mean PM_{10} levels of the five sites during dry and rainy seasons.

PM_{10} levels were higher during the dry than rainy season indicating that dry air with lower humidity aggregated the levels and caused higher pollutants that prevailed across the Athi River Municipality. On the other hand, the reduced PM_{10} levels during the rainy season could be as a result of wash-out effect of rainfall (Were *et al.* 2020). Research conducted by Prządka *et al*. (2012) and Radzka (2020) also revealed that the concentration of PM_{10} was season-related and was largely affected by meteorological factors. The highest standard error from the mean PM_{10} level (432.1±160.5) was observed in the industrial site ''A'' during the dry season shown in Figure 4.7 might have been influenced by a wide range of variation in the meteorological elements that were reported.

Overall, the study has showed that the levels of PM_{10} sampled for three hours in the morning and afternoon, respectively were high in the industrial sites, followed by commercial and residential areas regardless of the period of the day and season. Though, the levels obtained from this study cannot be directly compared with those of the Ambient Air Quality (AAQ) Regulation set by NEMA (2014) because of the differences in the sampling periods. The NEMA set limits is 100 and 150 $\mu g/m^3$ of PM_{10} levels for 24-hour average weighted time for residential and industrial sites, respectively. Notwithstanding the sampling periods, the levels obtained in this study markedly exceeded those of AAQ Regulation limit stipulated by NEMA (2014). This implies that the cement industries are major sources of PM_{10} in the communities. Previous studies are in agreement that elevated levels of PM_{10} is found in the communities in the vicinities of cement industries (Nkhama *et al*., 2015; Were *et al*., 2020).

4.7: Chemical composition of PM_{10}

The chemical compositions were evaluated for PM_{10} during the dry and rainy seasons. Figure 4.8 presents the elemental composition (%) of PM_{10} that was determined.



Note: sites: 1-Industrial "A", 2-Industrial "B", 3- Residential "A" , 4- commercial and 5-Residential "B"

Figure 4.8: Elemental composition (%) of PM_{10} at the sampled sites during dry and rainy seasons

The PM_{10} obtained at the five sites varied in percentage (%) composition of the eleven elements namely: Cu, Sb, Si, Al, Ca, Fe, Zn, Cr, Pb, Cd and Ni shown in Figure 4.8. Nonetheless, some elements were below the detection limit (BDL) of the EDXRF. For instance, Sb was only detected in industrial site "B'' and the commercial site during the dry season. In spite of that, elements such as Si, Cd, Al, Ca and Fe were detected in all the sampled sites in relatively high proportions irrespective of the seasons.

Silicon, aluminum and cadmium had the highest % composition in all sites during dry and rainy seasons. Industrial site ''A'' had the highest % composition of Si and Al as compared to the other sites during dry and rainy seasons. The highest % composition of Cd was exhibited in residential

site ‘‘A’’ for both seasons. Higher % composition of Si and Al that was observed during the rainy season than the dry season. This could be attributed to their oxides that do not dissolve in water hence they are not easily washed away and are consequently persistent in the environment. Moreover, high humidity during rainy season makes PM_{10} to gather mass and Al is amphoteric in nature and has colloidal properties. Overall, Si and Al are associated with dust re-suspension originating from cement industry.

The increase in Cd content during the rainy season could also be due to many of its compounds that are volatile and the condensation on aerosols which are common after emission processes caused by high temperatures. By this, they are left condensed on surface of particles hence increasing its bioavailability. The high Cd content in residential site ‘‘A’’ could be probably be as a result of many other sources which include Earth’s crust, vehicular emissions and coal from cement kiln. The high elemental % of Si, Cd, Al, Ca and Fe can be mainly associated with the cement industries that were in close proximity to the sampling sites. Conversely, other sources of these elements could be vehicular emissions, other industries that were present and earth’s crust for all the sampled sites.

Lead was highest in industrial site ‘‘A’’ during the dry season although it was below detection limit (BDL) in all sampled sites during the rainy season. It was also BDL in site ‘‘B’’ during the dry season but elevated in all other sites during the same period. Fugitive Pb appears together with crustal elements such as Si indicating that Pb is suspended (Harris and Davidson, 2005). Lead particles are produced during lead battery handling to reclaim lead (Glover *et al*., 1991). Main sources of Pb were vehicular emissions, steel production, cement coal kiln and battery recycling processes.

Residential site “A” had the highest % composition of Cr during the rainy season. Inhalable Cr may be produced from kiln in cement production, brake linings of automobiles and their catalytic converters. Nickel was highest in residential site ‘‘A’’ during the rainy season. Inhalable Ni may be produced from coal production and manufacturing factories. Zinc was also highest in residential site ‘‘A’’ during the rainy season. Particulate Zn mostly originates from wind erosion, fuel combustion, industrial metallurgical processes and is also associated with rubber abrasion (Councell *et al*., 2004). Residential site ‘‘A’’ had highest % of Cr, Ni and Pb due to its proximity to the cement industries. The wind direction that prevailed could also have caused PM_{10} levels to be blown towards the sampling site influencing the elemental composition. Residential site ‘‘A’’ location along the Makadara-Athi River road alongside many surrounding industries could all have contributed to the highest % composition of Cr, Zn and Ni during the rainy season. In addition, high RH could have contributed to the dust gathering mass and hence these components were not dispersed far away from their sources.

4.7.1: Health effects of elements contained in PM_{10}

The study found high % composition of Si, Cd, Al, Ca and Fe in the PM_{10} (Figure 4.8). These elements together with those that were in small amounts could be associated with adverse health effects when inhaled.

For instance, the inhalation of crystalline silica is a possible route of exposure that result in silicosis (NIOSH, 2002) and lung cancer (IARC, 2012). Research done between 2001 and 2010, found 1,437 decedents had silicosis and was coded as the underlying or contributing cause of death in the United States of America (Bang *et al*., 2015). It is also associated with chronic obstructive

pulmonary disease (COPD) and kidney disease (IARC, 2012). Aluminum dusts can cause lung conditions such as coughing and abnormal chest X-rays have been observed. Acute inhalation of Cd result in flu-like symptoms (chills, fever and muscle pain) and can damage lungs while chronic exposure is implicated in the kidney, bone or lung disease (Cooper and Harrison, 2009; Geiger and Cooper, 2010). On the hand Pb exposure can cause miscarriages, stillbirth and infertility for both genders (kumar, 2018). Although Pb was BDL in most sites, it should be noted that there is no safe level of Pb.

Chronic exposure to antimony may aggravate irritation of skin, eyes and lungs while chronic inhalation has the potential to cause pneumoconiosis, altered electrocardiograms, diarrhea and stomach pains (Geiger and Cooper, 2010). Iron dust can cause pneumoconiosis (siderosis) with cough, shortness of breath. On the hand, when Cr compounds are inhaled, they are responsible for respiratory tract irritation and can lead to pulmonary sensitization. Chronic inhalation of Cr (VI) has been hypothesized to increase the risk of lung, nasal, and sinus cancers (Geiger and Cooper, 2010). Nickel changes heart rate, partially due to the inhaled particles being able to create reactive oxygen species (ROS) (Zelikoff *et al*., 2002). Respiratory effects from Nil have been recognized as a carcinogen, giving rise to lung and nasal cancers. Short-term effects of inhalable Zn result in coughing and irritation of the upper respiratory tract. Zinc can also cause anosmia due to its damage on nerve receptors of the nose (Geiger and Cooper, 2010).

CHAPTER FIVE

CONCLUSIONS AND RECOMMEDATIONS

5.1: Conclusions

Arising from the results obtained in this study, the mean PM_{10} levels were high and varied across the sampling sites with industrial sites reporting the highest levels, followed by commercial site and then residential sites regardless of the time of sampling and seasons. The concentrations of PM_{10} were also significantly ($p < 0.05$) higher during the dry than the rainy season. Furthermore, the levels of PM_{10} were much higher ($P< 0.05$) during the morning than afternoon period irrespective of the season.

The PM_{10} levels were strongly influenced by the meteorological elements that included wind speed, relative humidity, wind direction and temperature. There was a positive correlation between relative humidity and PM_{10} concentration while temperature and wind speed had a negative correlation with PM_{10} levels when Pearson's correlation coefficient was applied. Levels of PM_{10} were significantly higher in the residential area that was situated downwind the direction of the industries compared to that of upwind, implying that wind speed and direction influenced levels of PM_{10} levels. The PM_{10} levels were markedly higher during the dry season than during the rainy season.

The elemental composition (%) of PM_{10} also varied s across the seasons and sampling sites and reflected the components of cement, which were mainly calcium, silicon, aluminum and iron.

5.2: Recommendations

Based on the data that was obtained in this study, the recommendations are as follows:

i. Frequent monitoring of particulate matter should be conducted to ensure that the levels of PM_{10} are controlled.

ii. The cement industries should put in place suitable pollution control systems to protect the health of the residents around the cement industries.

iii. National Environment Management Authority (NEMA) should ensure that the cement industries adhere to the environmental regulations.

iv. The cement industries should not be within the vicinity of residential areas to reduce the levels of exposure to toxic particulate matter.

v. Further investigation on $PM_{2.5}$ or lower aerosols should be carried out and their associated health effects.

vi. More studies should be conducted to assess the indoor and outdoor exposure to air pollution with a special focus on vulnerable groups such as infants, the elderly and those suffering from other pre-existing conditions.

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APPENDICES

Appendix 1: Net weight, total volume and levels of PM_{10} collected for three (n = 3) consecutive days in the morning and afternoon during the dry and rainy seasons across different sites (n = 5) around cement industries in Athi River Municipality in Machakos County

Season	Sampling Site	Period of the day	Total volume of air (m^3)	PM_{10} net weight (g)	Levels ($\mu g/m^3$)	Date
Dry season	Industrial "A"	AM	0.54	0.00040	740.7	20/2/2019
		PM	0.54	0.00017	314.8	20/2/2019
		AM	0.54	0.00026	481.5	21/2/2019
		PM	0.54	0.00015	222.2	21/2/2019
		AM	0.54	0.00030	555.6	22/2/2019
		PM	0.54	0.00012	277.8	22/2/2019
	Industrial "B"	AM	0.54	0.00020	370.4	26/2/2019
		PM	0.54	0.00013	240.7	26/2/2019
		AM	0.54	0.00026	481.5	27/2/2019
		PM	0.54	0.00012	222.2	27/2/2019
		AM	0.54	0.00019	351.9	28/2/2019
		PM	0.54	0.00010	185.2	28/2/2019
	Residential "A"	AM	0.54	0.00012	222.2	5/3/2019
		PM	0.54	0.00006	111.1	5/3/2019
		AM	0.54	0.00014	259.3	6/3/2019
		PM	0.54	0.00008	148.1	6/3/2019
		AM	0.54	0.00014	259.3	7/3/2019
		PM	0.54	0.00007	129.6	7/3/2019
	Commercial	AM	0.54	0.00023	425.9	12/3/2019
		PM	0.54	0.00011	203.7	12/3/2019
		AM	0.54	0.00019	351.9	13/3/2019
		PM	0.54	0.00007	129.6	13/3/2019
		AM	0.54	0.00018	333.3	14/3/2019
		PM	0.54	0.00008	148.1	14/3/2019
	Residential "B"	AM	0.54	0.00020	370.4	10/9/2019
		PM	0.54	0.00010	185.2	10/9/2019
		AM	0.54	0.00016	296.3	11/9/2019
		PM	0.54	0.00009	166.7	11/9/2019
		AM	0.54	0.00018	333.3	12/9/2019
		PM	0.54	0.00010	185.2	12/9/2019

Season	Sampling Site	Period of the day	Total volume of air (m^3)	PM_{10} weight (g)	Levels ($\mu g/m^3$)	Date
Rainy season	Industrial "A"	AM	0.54	0.00017	314.8	8/5/2019
		PM	0.54	0.00009	166.7	8/5/2019
		AM	0.54	0.00019	351.9	9/5/2019
		PM	0.54	0.00011	203.7	9/5/2019
		AM	0.54	0.00013	240.7	10/5/2019
		PM	0.54	0.00007	129.6	10/5/2019
	Industrial "B"	AM	0.54	0.00017	314.8	14/5/2019
		PM	0.54	0.00010	185.2	14/5/2019
		AM	0.54	0.00014	259.3	15/5/2019
		PM	0.54	0.00008	148.1	15/5/2019
		AM	0.54	0.00014	259.3	16/5/2019
		PM	0.54	0.00007	129.6	16/5/2019
	Residential "A"	AM	0.54	0.00007	129.6	21/5/2019
		PM	0.54	0.00003	55.6	21/5/2019
		AM	0.54	0.00005	92.6	22/5/2019
		PM	0.54	0.00002	37.0	22/5/2019
		AM	0.54	0.00006	111.1	23/5/2019
		PM	0.54	0.00002	37.0	23/5/2019
	Commercial	AM	0.54	0.00016	296.3	28/5/2019
		PM	0.54	0.00006	111.1	28/5/2019
		AM	0.54	0.00011	203.7	29/5/2019
		PM	0.54	0.00004	74.1	29/5/2019
		AM	0.54	0.00013	240.7	30/5/2019
		PM	0.54	0.00004	74.1	30/5/2019
	Residential "B"	AM	0.54	0.00013	240.7	14/10/2019
		PM	0.54	0.00005	92.6	14/10/2019
		AM	0.54	0.00010	185.2	15/10/2019
		PM	0.54	0.00004	74.1	15/10/2019
		AM	0.54	0.00009	166.7	16/10/2019
		PM	0.54	0.00003	55.6	16/10/2019

Appendix 2: Meteorological factors that prevailed during the sampling period (n =3) in five sites in the morning and afternoon for the dry and rainy seasons in Athi River Municipality in Machakos County

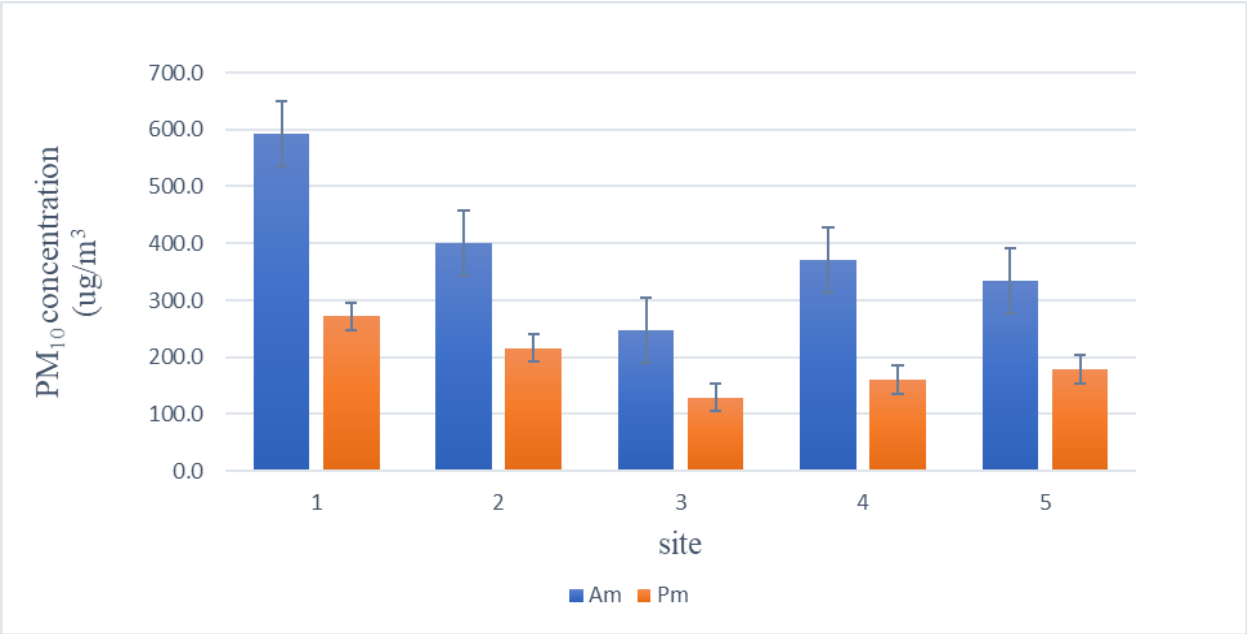
Season	Sampling Site	Period of the day	Wind speed (m/s)	Wind direction	Relative humidity (%)	Temperatures (^{0}C)	Date
Dry season	Industrial "A"	AM	3.3	ENE	73	21	20/2/2019
		PM	4.4	ENE	64	25	20/2/2019
		AM	4.4	E	61	24	21/2/2019
		PM	5.3	ENE	43	29	21/2/2019
		AM	3.9	NE	68	22	22/2/2019
		PM	5	ENE	58	27	22/2/2019
	Industrial "B"	AM	5	ENE	57	22	26/2/2019
		PM	5.8	ENE	44	25	26/2/2019
		AM	5.6	NE	45	24	27/2/2019
		PM	6.4	ENE	36	28	27/2/2019
		AM	5.3	ENE	52	23	28/2/2019
		PM	6.1	NE	42	26	28/2/2019
	Residential "A"	AM	3.9	NE	52	21	5/3/2019
		PM	4.7	ENE	46	25	5/3/2019
		AM	5.3	ENE	50	23	6/3/2019
		PM	5.6	E	39	28	6/3/2019
		AM	5	ENE	45	24	7/3/2019
		PM	5.3	ENE	36	29	7/3/2019
	Commercial	AM	5.3	NE	52	21	12/3/2019
		PM	6.4	ENE	38	24	12/3/2019
		AM	3.9	ENE	48	24	13/3/2019
		PM	6.1	NE	37	28	13/3/2019
		AM	5	ENE	50	23	14/3/2019
		PM	5.8	ENE	36	29	14/3/2019
	Residential "B"	AM	5	NE	55	23	10/9/2019
		PM	6.1	ENE	38	27	10/9/2019
		AM	5.6	NE	53	22	11/9/2019
		PM	6.4	ENE	36	28	11/9/2019
		AM	3.9	NE	56	24	12/9/2019
		PM	5.3	ENE	41	29	12/9/2019

Season	Sampling Site	Period of the day	Wind speed (m/s)	Wind direction	Relative humidity (%)	Temperatures (^{0}C)	Date
Rainy season	Industrial "A"	AM	2.8	ESE	81	18	8/5/2019
		PM	3.3	ESE	72	21	8/5/2019
		AM	3.6	ESE	65	20	9/5/2019
		PM	4.2	ESE	61	22	9/5/2019
		AM	2.2	S	88	16	10/5/2019
		PM	3.1	E	77	20	10/5/2019
	Industrial "B"	AM	2.2	SE	77	19	14/5/2019
		PM	3.1	ESE	66	22	14/5/2019
		AM	3.3	SSE	71	21	15/5/2019
		PM	3.9	SSE	56	23	15/5/2019
		AM	3.1	SSE	71	21	16/5/2019
		PM	3.6	ESE	74	20	16/5/2019
	Residential "A"	AM	2.8	ESE	81	17	21/5/2019
		PM	3.1	ESE	70	19	21/5/2019
		AM	2.8	ESE	57	19	22/5/2019
		PM	3.3	ESE	49	22	22/5/2019
		AM	2.2	S	55	20	2135/2019
		PM	3.1	E	48	24	23/5/2019
	Commercial	AM	3.1	ESE	62	20	28/5/2019
		PM	3.9	E	60	23	28/5/2019
		AM	2.5	SSE	80	17	29/5/2019
		PM	3.6	ESE	76	19	29/5/2019
		AM	2.8	ESE	73	20	30/5/2019
		PM	3.1	ESE	69	19	30/5/2019
	Residential "B"	AM	3.1	ESE	71	20	14/10/2019
		PM	3.6	SSE	66	21	14/10/2019
		AM	1.9	SSE	74	18	15/10/2019
		PM	2.5	SSE	70	20	15/10/2019
		AM	2.2	S	77	17	16/10/2019
		PM	3.3	SE	69	19	16/10/2019

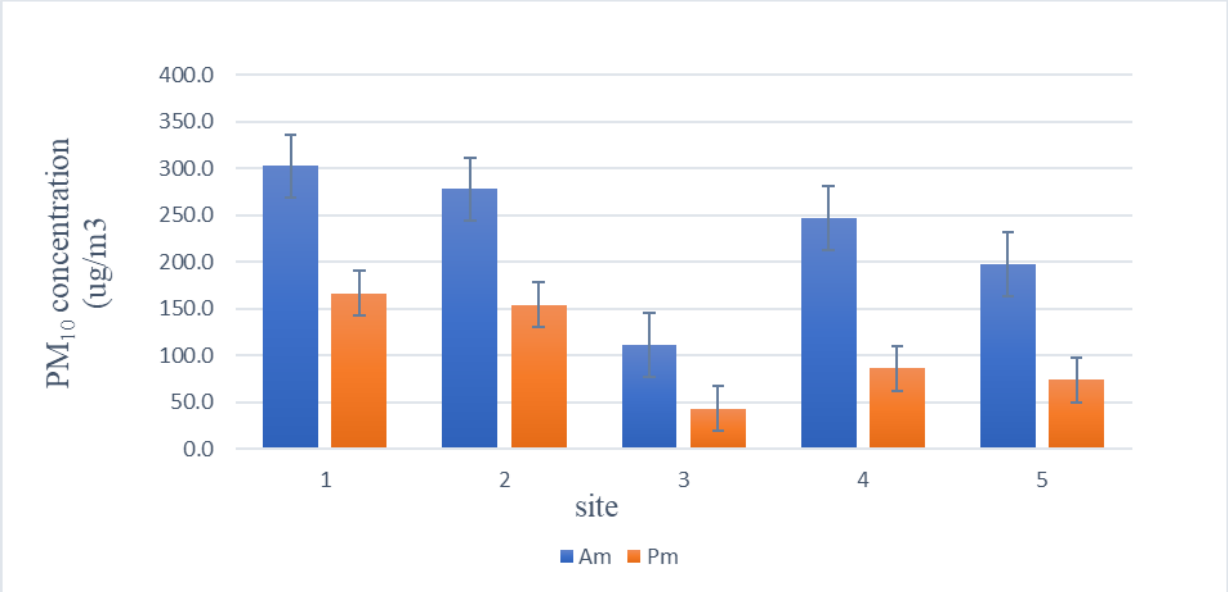
Appendix 3: Mean (±SD) levels of PM_{10} and meteorological factors sampled from five sites in the afternoon and morning for three consecutive days per site during the dry and rainy seasons in Athi River Municipality in Machakos County

Seasons	Mean (±SD) levels of PM_{10} and meteorological factors					
	Sampling Site	Period of the day	PM_{10} concentration ($\mu g/m^3$)	Wind speed (m/s)	Relative humidity (%)	Temperatures (^0C)
Dry	Industrial "A"	AM	592.6±133.5	3.9±0.6	67.3±6.0	22.3±1.5
		PM	271.6±46.6	4.9±0.5	55±10.8	27±2.0
	Industrial "B"	AM	401.2±70.1	5.3±0.3	51.3±6.0	23±1.0
		PM	216.0±28.3	6.1±0.3	40.7±4.2	26.3±1.5
	Residential "A"	AM	246.9±21.4	4.7±0.7	49±3.6	22.7±1.5
		PM	129.6±18.5	5.2±0.5	40.3±5.1	27.7±2.1
	Commercial	AM	370.4±49.0	4.7±0.7	50.0±2.0	22.7±1.5
		PM	160.5±38.6	6.3±0.3	37.0±1.0	27±2.6
	Residential "B"	AM	333.3±37.1	4.8±0.9	54.7±1.5	23±1.0
		PM	179.0±10.7	5.9±0.6	38.3±2.5	28±1.0
Rainy	Industrial "A"	AM	302.5±56.6	2.9±0.7	78±11.8	18.0±2.0
		PM	166.7±37.1	3.5±0.6	70.0±8.2	21.0±1.0
	Industrial "B"	AM	277.8±32.1	2.9±0.6	73.0±3.5	20.3±1.2
		PM	154.3±28.3	3.5±0.4	65.3±9.0	21.7±1.5
	Residential "A"	AM	111.1±18.5	2.6±0.3	64.3±14.5	18.7±1.5
		PM	43.2±10.7	3.2±0.1	55.7±12.4	21.7±2.5
	Commercial	AM	246.9±46.6	2.8±0.3	71.7±9.1	19.0±1.7
		PM	86.4±21.4	3.5±0.4	68.3±8.0	20.3±2.3
	Residential "B"	AM	197.5±38.5	2.4±0.6	74.0±3.0	18.3±1.5
		PM	74.1±18.5	3.1±0.6	68.3±2.1	20.0±1.0

Appendix 4: Graph of PM_{10} mean (±SD) levels in the morning and afternoon during the dry season against different sampling sites



Appendix 5: Graph of PM_{10} mean (±SD) levels in the morning and afternoon during the rainy season against different sampling sites.



Appendix 6: Acquisition of meteorological data from the Meteorological Department in the Ministry of Environment and Forestry

KENYA METEOROLOGICAL DEPT.
P. O. Box 30259 - 00100, G.P.O
NAIROBI

REPUBLIC OF KENYA

KENYA METEOROLOGICAL DEPARTMENT
MINISTRY OF ENVIRONMENT & FORESTRY

Dagoretti Corner, Ngong Rd, P. O. Box 30259-00100 GPO, NAIROBI, Kenya.
Tel: +254-20-3867880-7; Fax: +254-20-3876955
e-mail: director@meteo.go.ke, info@meteo.go.ke, Website: http://www.meteo.go.ke

INVOICE No. 7/9/562/5/19

M/S: University of Nairobi 15th May, 2019

Attention: Dr. Faridah Hussein Were

ITEM	Particulars	Rate Kshs.	Amount Due Kshs
	Extraction of Data for JKIA Meteorological station		
	Masters Student	6000*1	6,000.00
		Amount Due	**6,000.00**

For: DIRECTOR OF METEOROLOGICAL SERVICES

Payment to be made to:-
Meteorological Department
P. O. Box 30259-00100, Nairobi.
Bank: Kenya Commercial Bank
Branch: Kipande House Branch, Kenyatta Avenue
Account Number: 241970181
Swift Code: KCB LKENX
Bank Code: 4008

For DIRECTOR
KENYA METEOROLOGICAL DEPARTMENT
P. O. Box 30259 - 00100, G.P.O
NAIROBI