Air pollution study in Northwest Africa; case of the urban city of Bamako in Mali

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In the memory of the Love of my life

Mariam Dienta

You taught me that love is infinity

♥

Abstract

The exposure to air pollution in indoor and outdoor microenvironments is a major health risk factor. Especially in developing regions where; modern and cleaner households' energy such as natural gas and electricity are not widely accessible. Plus, the traffic sector is dominated by aging vehicles and motorbikes. In the urban regions of African cities, including Bamako (the capital city of Mali) the population growth and the attendant requisites result in high pollutants emission. However, information on the air condition over Bamako is very scarce due to difficulties such as: the lack of human, technical and financial resources. The present thesis addresses this. Bamako's population daily exposure to $PM_{2.5}$; one of the greatest health affecting pollutants was determined for the first time. To achieve this, local inhabitants carried palm-size optical sensors during their daily activities. The exposure concentrations exceeded the WHO daily and yearly standards of 25 $\mu g/m^3$ and 10 $\mu g/m^3$ respectively. A relationship was evident between the daily activities and the exposure level. The highest exposure concentrations were observed during the indoor combustion of insecticide (IST) and incense (ICS). The values were up to 999 $\mu g/m^3$ and 145 $\mu g/m^3$ respectively. Flowed by traffic (216 $\mu g/m^3$) and cooking (150 $\mu g/m^3$). These were therefore determined as the most exposing activities and/or microenvironment in this region. Additionally, PM was sampled on quartz and Teflon filters to characterize the chemical composition and determine the health risks from the exposure to PM emitted from the typical daily activities; cooking emissions, traffic emissions and households' IST and ICS products combustion. The composition varied from an emission source to another. The health risk assessment study revealed that in addition to the high concentration, the PM emitted from the common daily activities were toxic to human health. The source distribution study of ambient PM indicated that dust resuspension was the greatest contributor to outdoor PM pollution (70 %). Biomass burning and traffic emissions also had significant contributions. The concentration of major ambient air pollutants including NO_2, O_3, SO_2, CO, $PM_{2.5}$, PM_{10} were measured over 6 moths. The concentrations were very high and there was a notable

difference between the observed concentrations during the rainy and dry season. Daily anthropogenic activities were the main sources of air pollution. The relationship between pollutants concentrations and meteorological condition such as wind speed and humidity indicated that local conditions had an influence on the air condition. Moreover, in this research, we conducted a survey on the perception of the population on air pollution. The results demonstrated that although the respondents' perception of air pollution source differed from the actual emission sources in Bamako city, more than half were aware of air pollution. They reported discomforts due to the air condition and the need of a cleaner air. This thesis provided for the first-time valuable information on indoor and outdoor air pollution level as well as the exposure risks in the urban city of Bamako. Furthermore, it provided information the emissions sources related to the common daily activities and discussed the possible mitigation strategies. Overall, the findings indicated the urge of promptly elaborating and applying air pollution mitigation strategies in Bamako City.

Keywords: Bamako, urban air pollution, anthropogenic activities, insecticides and incense, traffic, exposure risks

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List of abbreviations

ACAP	Asian Center for Air Pollution research
Adl	Adult
amb	Ambient air
AQT	Air Quality Transmitter
Asso	Associations
BS	Beauty Salon
CO	Commute
CHL	Charcoal cooking
Chl	Children
CK	Cooking
CMB	Chemical Mass Balance
COOK	Cook
CR	Carcinogenic Risk
DRI 2001	Desert Research Institute Model 2021
DRI	Drivers
Drv	Driving
EC	Elemental Carbon
EF	Enrichment Factor
HI	Hazard Index
HO	Home
HQ	Hazard Quotient
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICS&Chl	Incense and Charcoal
ICS	Incense
IST	Insecticides
Max	Maximum
MB	Motorbike

Med	Median
Min	Minimum
Mrt	Market
N-gas	Natural gas
nd	Not Detected
OA	Other activities
OC	Organic Carbon
OPC	Optical Particle Counter
Orga	Organization
OW	Office Workers
PC	Personal Car
PCA	Principal Component Analysis
PM	Particulate Matter
PM_{10}	Particulate matter with a diameter less 10 micrometers
$PM_{2.5}$	Particulate matter with a diameter less or equal to 2.5 micrometers
PT	Public Transportation
Q1	First quartile
Q3	third quartile
Rds	Roadside
SB	School (break)
SC	School (classes)
SDG	Sustainable Development Goals
SOTAMA	Société des transports du Mali (Transport Company of Mali)
ST	Student
T-CR	Total Carcinogenic Risk
WHO	World Health Organization
Wood	Wood cooking
WP	Workplace

General Introduction

It is clear that air is a major element in human's life. An evidence of the importance of this natural resource is that, we can't live without breathing. Every human being needs oxygen (O_2) to live; which is one of the main components of the air we breathe. Unfortunately, unlike water which is a natural resource as well, ambient air is directly breathed without any pretreatment. A bad air quality represents major risks. Not only for humans and animals' health but, also has harmful effects on the environment around them.

Air quality is a complex issue and, it is influenced by a variety of factors. The term air quality refers to the degree to which the air in a particular place is free from pollutants. Air pollutants are substances present in the atmosphere at concentrations above their normal background levels which can have significant effects on the living organism and their ecosystems [8]. Air pollutants can originate from anthropogenic sources or natural sources. Fuel combustion for power generation, transport and other anthropogenic activities produce various pollutants such as sulfur dioxide (SO_2) that are directly emitted from combustion sources, nitrogen oxides (NOx) and carbon monoxide (CO), as well as pollutants formed by reactions between those directly emitted, such as ozone (O_3). Particulate matters (PM) are from both origins, they can be solid, liquid in suspension in a gas. PM can be classified by sizes, such as PM_{10}, $PM_{2.5}$ or ultra-fine particles [9]. Fine particles have been clearly linked to the most serious health problems. Epidemiological studies have shown a clear association between PM and cardiovascular morbidity, decreased lung function, increased hospital admissions, mortality [10] [11]. Up to 14% of children under 18 years old have health issues related to air pollution. Air pollution is also linked to childhood cancers and to cognitive impairment in both children and adults. Every

year, 543 000 children under 5 years old die from respiratory disease linked to air pollution. Furthermore, exposure to air pollution during pregnancy have effects on fetuses [12].

Africa nowadays is one of the most polluted continents in the world. This pollution is greatly increasing throughout the years. Since all the compartments of the environment; air, water and soil intercommunicate, it affects all these compartments. Although, air pollutants generates from natural sources such as volcanic eruptions, natural fires, Africa's fast-growing population and the attendant requisites is the main cause of the increasing pollution. Urban cities, facing strong rural exodus are the most affected. Tremendous chemicals are released in the environment to provide these developing populations basics needs such as nutrition, housing, clothing, transportation. It is important to know that the air in urban areas is more polluted than the air in rural areas due to multiple human daily activities. According to the WHO (World Health Organization), more than 80% of urban areas have exceeded the standards of air quality recommended for health safety. Between 1990 and 2013, the total number of annual deaths due to outdoor air pollution; ambient particulate pollution, mostly from road transportation, power generation or industry increased by 36%. Over the same period of time, deaths due to household air pollution caused by the use of polluting forms of household energy increased by 18%. According to the WHO's report, about 7 million of people are dying each year due to the pollution and, most of this number 90% are in low-and middle-incomes countries [13]. The organization estimates that Africa has more than a million deaths due to air pollution. In fact, the economic situation of a country is a contributing factor increasing the pollution's level and, the pollution plays a role in the economy and the agriculture. This results in a cycle worsening both pollution and economic problems. Low-income countries use available naturals resources (wood for instance), chemical fertilizers and pesticides for agriculture. However, the legislation regarding environmental pollution is less strict and, the environmental pollution management system is not adequate. Therefore, human activities contribute to the increase of the pollution level which has effects on the entire biosphere.

The acute level of atmospheric pollution is no longer a minor issue that can wait to be ad-

dressed. Atmospheric pollutants have been increasing from decades all around the world. In West Africa, air pollution has reached a very alarming level because it affects the population in a daily basis and in different ways.

However, the information on air pollution is very scarce. This study was designed to provide background information on air pollution in Bamako, Mali. As many other developing cities, in Bamako, the vehicle fleet is one of the most important pollution factors. In 2019, 76% of the registered vehicles in Mali were listed in Bamako city which makes it more subject to urban air pollution [14]. Second-hand cars mostly from Europe (Belgium, Germany, France), are sold to African countries. Moreover, most of the population use two-wheels and three wheels vehicles; motorbikes from China. Economically more suitable for the majority of the population, in terms of both price and maintenance (such as fuel consumption, mechanical problems), these engines release considerably more pollutants in the environment. Another main factor of air pollution in Bamako-Mali is the waste management system. Wastes are generally collected, transported and transferred at dumping sites where, they are usually incinerated during the dry season.

PM are known for their multiple and effects on the health and environment. In this study, we focused on the investigation of the population exposure to PM and the quantification the major atmospheric pollutants in Bamako city. The main questions of the research were:

1) What are the main exposure sources to PM in Bamako's inhabitants?

2) What is the chemical composition of PM released from typical daily activities in Bamako and the associated health risks?

3) What is the level of major pollutants at typical roadside in Bamako?

4) What is the population perception about air pollution?

The first chapter of this study entitled Urban atmospheric pollution in West Africa and con-

sequences focuses on air pollution in urban areas. It first gives a general overview of the major air pollutants; origin and fate, possible impacts. Then addressed air pollution in West Africa. The second chapter explains the study design and methodology. It describes the study area and sampling sites, provides information on the sampling procedures and analytical techniques. The third chapter presents the findings. The results provided useful information on the exposure to $PM_{2.5}$ as well as the relationship between the exposure level and the daily activities. Characterized the composition of PM from different emission sources and the possible health risks associated with the exposure. Provided information on sources of ambient air pollution in Bamako city. And, gave insights into the population's knowledge on air pollution emission and exposure sources. The last chapter contains recommendations and general conclusion.

Chapter 1

Urban atmospheric pollution in West Africa and consequences

Urban atmosphere can be referred as all the molecules that surround humans living environment; those naturally present and those released from anthropogenic activities. Urban air quality can be referred as the cleanness of the ambient air inside cities where anthropogenic actives can be observed. Since the industrial revolution, human activities have exponentially grown and air quality have been continuously decreasing. This results to the current urban air quality level worldwide. The life quality of millions of people is significantly affected by urban air pollution especially in developing cities. Urbanization, industrialization and traffic have resulted in the increase of air pollution in densely populated areas, causing deterioration in air quality [15]. More than 80% of urban cities have higher air pollution level then the limits recommended for the health reasons [16]. WHO estimates that 23 per cent of global deaths (12.6 million) is linked to environmental factors. Air pollution is responsible for 7 million deaths every year out of the 12.6 million [17]. It is a major challenge in Africa. The effects on health can be felt by the gradual increase in the number of patients and diseases. About 600,000 deaths every year across the African continent is attributed to the air quality [18]. In West African urban cities, fuel combustion, biomass combustion and the developing industries seem to be the predominant sources of air pollution. These sources are becoming more important with the fast-growing population.

1.1 Atmospheric pollution

Atmosphere is defined as the gaseous envelope surrounding the Earth [7]. In Greek atmos means ' vapour ', and sphaira, means 'ball' or 'sphere [19]. Human and other living organisms can live on Earth because it has an atmosphere; its moderates daytime and nighttime temperature swings. The atmosphere filters daytime solar radiant energy to prevent the surface from overheating and keeps the surface warm at night, preventing a large part of the radiant heat from escaping back into space [7].

Pollutants can generate from diverse sources. Pollution comes from nearly all human daily activities; the traffic sector, the industrial activities, the agricultural activities, urbanization and construction activities, natural resources exploitation, energy production and consumption, hus-

bandry breeding and so on. Natural occurring pollution is generated from sources such as wind erosion, sea spray, and volcanic eruption. Another known natural pollution source is the biogenic source referring to biological organisms' natural activities such as bacterial decomposition. All of these sources contribute to the high level of pollution all over the world. In urban environment, pollutants such as ozone (O_3), carbon monoxide (CO), Nitrogen oxides (NOx), Sulfur dioxide (SO_2), particulate matter with a diameter less or equal to 2.5 and 10 micrometers ($PM_{2.5}$ and PM_{10}) are common major atmospheric pollutants.

1.2 Atmospheric composition and structure

Atmosphere is a relatively stable mixture of several types of gases from different origins some with fairly constant concentrations and others that are variable in space and time (Table1.1).

Table 1.1: Major constituents of the Earth's atmosphere up to 100 km (dry air). Adopted from [7]

	Constituents	Percentage by volume	Molecular weight (g mol^{-1}
(A)	*Constant concentrations*		
	Nitrogen (N_2)	78.08	28.01
	Oxygen (O_2)	20.95	32.00
	Argon (Ar)	0.933	39.95
	Carbon dioxide (CO_2)	0.033	44.1
	Neon (Ne)	18.2 x 10^{-4}	20.18
	Helium (He)	5.3 x 10^{-4}	04.02
	Krypton (Kr)	1.1 x 10^{-4}	83.80
	Xenon (Xe)	0.089 x 10^{-4}	131.29
	Hydrogen (H_2)	0.5 x 10^{-4}	02.02
	Methane (CH_4)	1.5 x 10^{-4}	16.04
	Nitrous oxide (N_2O)	0.27 x 10^{-4}	44.01
	Carbon monoxide (CO)	0.19 x 10^{-4}	28.01
(B)	*Variable concentrations*		
	Water vapor (H_2O)	0-4	18.02
	Ozone (O_3)	0-4 x 10^{-4}	48.02
	Ammonia (NH_3)	0.004 x 10^{-4}	17.02
	Sulphur dioxide (SO_2)	0.001 x 10^{-4}	64.06
	Nitrogen dioxide (NO_2)	0.001 x 10^{-4}	46.05
	Other gases	Trace amounts	
	Aerosols, dust, gases	Highly variable	

Nitrogen, oxygen, and argon account for about 99.96% of the permanent gases. Of the variable constituents, carbon dioxide, a well-known greenhouse gas can be somewhat variable in concentration on a localized basis at low levels. Water vapor is a major greenhouse gas and is a highly variable constituent. Its concentrations range from nearly zero in the coldest and dry regions of the atmosphere up to 4% by volume in hot and humid air masses. Ozone, an other major greenhouse gas, also varies distinctly. In addition to these variable constituents there are also aerosols, dust and gases which can vary widely in space and time [7].

Our atmosphere has different layers that can distinguished by the variation of temperature with the altitude (Figure1.1). The lowest layer; where we live is called troposphere. It starts from the earth surface up about 10 kilometers. In the troposphere, the temperature generally falls with the increasing altitude except when there are temperature inversions [1].

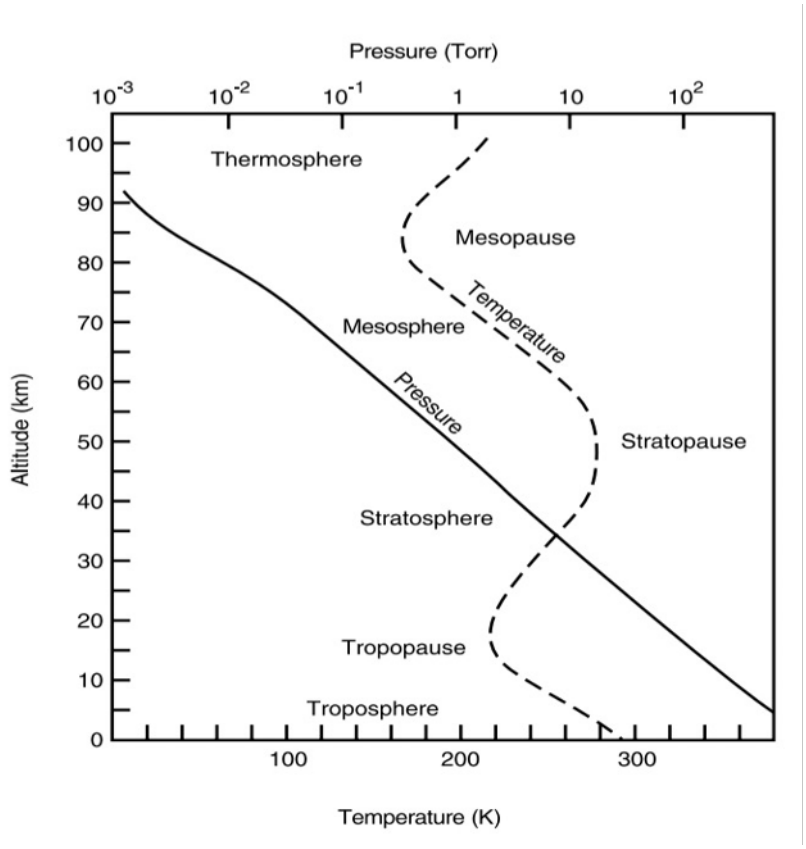


Figure 1.1: Structure of the atmosphere. Adopted from [1]. The atmosphere is composed of several different layers at different altitudes

The stratosphere is found above the tropopause and extends up to a height of 50 km. The

stratosphere is separated from the troposphere by the tropopause where, the temperature increases with the altitude throughout the stratosphere. This region is very important for life on earth as it is rich in ozone (O_3) absorbing harmful ultraviolet radiation from the sun. This ozone is the reason why the temperature increases in this region. The next layer is called mesosphere up to 85 kilometers where, the temperature decreases again due to the decrease of O_3 concentration. The transition layer between stratosphere and mesosphere is called stratopause. Thermosphere lays on top of the mesosphere from 85 kilometers. The region separating these two layers is called mesopause. Thermosphere is characterized by an increasing temperature due to the intense solar radiations. The upper layer is the exosphere. It is the most distant from the earth and gradually merges with the outer space. Compared to the other layers, very little is known about exosphere [1] [20]. As we interact the most with the first two layers (troposphere and stratosphere), they are the concern in most air pollution researches.

1.3 Process influencing air pollution

Air pollution can be affected by natural and unnatural processes and factors that characterise the re-partition of pollutants, the nature and the level of the pollution. Pollutants can undergo transformations and be carried away from their emission sources. Here we will focus on four main processes; emission, transport, chemical reaction and deposition (Figure 1.2 and A.1).

Emissions

Pollutants are emitted into the atmosphere from diverse sources as stated above. Anthropogenic emissions, such as burning fossil fuel. Biogenic emissions such as microbial breakdown of organic materials. Natural nonliving emissions, notably volcanic eruptions and desert dust. Once emitted, most pollutants are transported and undergo reactions to produce other pollutants.

Transport and dispersion

Emitted, pollutants are subject to dispersion and transport. Air pollution is not only determined by the type and intensity of the emissions. Meteorology and the climate, as well as the topography of the site, all have a major influence on the transport and dispersion. Transport is movement caused by a time-averaged wind flow [21] [22]. Winds can carry pollutants far from

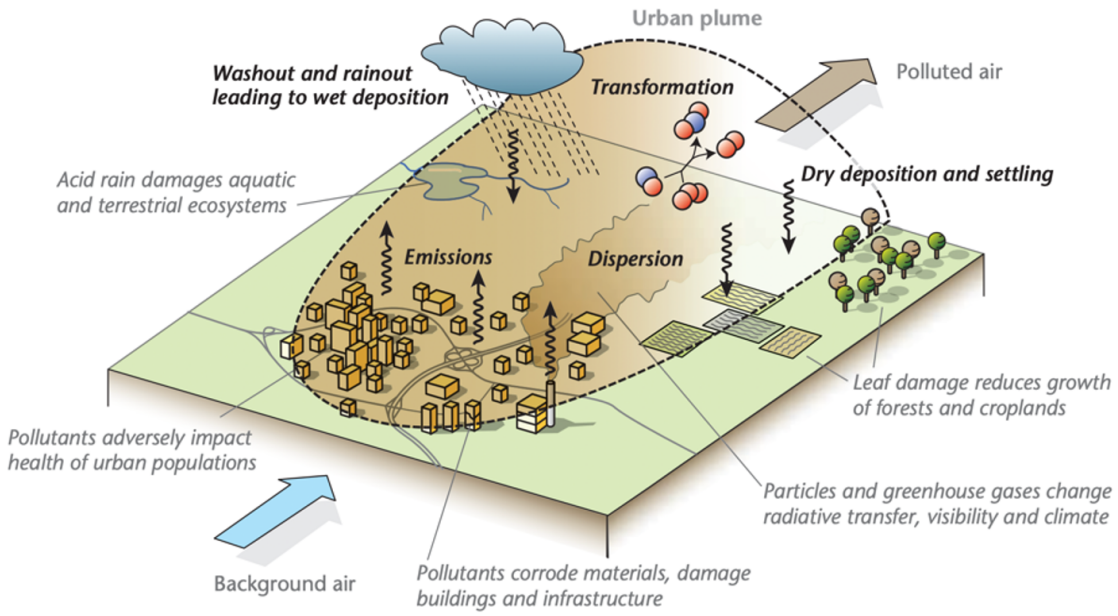


Figure 1.2: Process influencing air pollution in urban plume
Process regulating air pollution concentration in black and impacts of pollutants in grey.

their emission sources, so that emissions in one region cause environmental impacts far away. Short and long-range transport can result in a change of pollutants concentration and complicates efforts to control air pollution. Because it can be hard to distinguish effects caused by local versus distant sources and to determine who should bear the costs of reducing emissions [19]. Dispersion increases with the speed and turbulence of the wind, and its direction orients the pollutants.

Chemistry

Many types of chemical reactions in the atmosphere create, modify, and destroy chemical pollutants. Air pollutants undergo many complex reactions in the atmosphere and their residence times vary widely [19]. The vertical temperature gradient helps ascending movement of air pollutants. However, in case of temperature inversion, pollutants are blocked in the low layers of the atmosphere, which creates episodes of pollution. The transformation of air pollutants is influenced by temperature, humidity and solar rays.

Deposition

Deposition processes, including precipitation, scavenging, and sedimentation, cause downward movement of pollutants in the atmosphere, which ultimately remove the pollutants to the

ground surface [21]. Some materials in the atmosphere return to Earth, either because they are directly absorbed or taken up in a chemical reaction (such as photosynthesis) or because they are scavenged from the atmosphere and carried to Earth by rain, snow, or fog [19]. They can deposit onto soil or surface water, where they are absorbed by plants and ingested by animals. Therefore, they are introduced into the food chain [22].

1.4 Principal atmospheric pollutants

Atmospheric pollutants can be found in solid, gaseous and liquid form. They can be classified as primary or secondary pollutants. Primary pollutants differ from secondary pollutants as they are directly released from pollution sources. They are usually found in higher concentration near the emission sources. The secondary pollutants are generated from the reaction between the primary ones. Scientists have identified main pollutants, detrimental for human's health. Bellow a brief description of the main primary and secondary pollutants measured in this research.

Nitrogen oxides (NOx)

Diatomic molecular nitrogen (N_2) is a relatively inert gas that makes up about 80% of the air we breathe. However, the chemical element nitrogen (N), as a single atom, can be reactive with oxygen and hydrogen under high temperature conditions and, produce nitrogen oxides (NOx) or ammonia (NH_3) [23]. Nitrogen oxides (NOx) in the ambient air consist primarily of nitrogen oxide (NO) and nitrogen dioxide (NO_2). These two forms of gaseous nitrogen oxides are produced from natural sources and fuel burning processes. NO is colorless and odorless. It is oxidized in the atmosphere to form NO_2, an odorous, brown, acidic gas that can affect human health and environment. Nitrogen oxides are significant pollutants of the lower atmosphere [24]. They are important components of photo-chemical smog [25]. In presence of air and ultraviolet light nitrogen oxides are critical for generating ozone (O_3) and the hydroxyl radical (OH). The two most important tropospheric oxidants [26]. NO_2 was measured in this research.

Sulfur dioxide (SO_2)

Sulfur dioxide is a primary pollutant composed of molecules of sulfur and oxygen. It is a colorless gas with a sharp irritating odor. It is very readily soluble in water. SO_2 generates from industries such as metal extraction, traffic and any sulfur-containing fuels combustion [27]. Erupting volcanoes can be a significant natural source of sulfur dioxide. It is an important source of secondary organic aerosol (SOA) formation through photochemical reactions. SO_2 can also contribute to acid rain formation and toxic to human and plants [25].

Carbon oxides (COx)

Carbon oxides (COx) are formed of carbon and oxygen atom. Carbon oxides (CO, CO_2) are colorless and odorless and result from the combustion of fossil fuel such as traffic and cooking stoves and, natural processes such as vegetation degradation, wildfires and volcanoes. CO can be harmful at high concentration by reducing the amount of oxygen in the blood stream. CO_2 does not directly affect human health but it is known to be a major greenhouse gas. Furthermore, CO is a main precursor of tropospheric O_3 formation [28].

Particle matters (PM)

Particle matters (PM) also known as aerosols can be defined as small droplets of solids or liquids in suspension in a gas, mostly referred as atmosphere. Naturally present in in very small quantities or introduced by human activities in our living environment, PM can be found in various forms; dust, fume, smoke, mist, fog, haze, and smog [9]. Aerosols have different shapes and, sizes from less than one nanometer to thousands of microns. As many other air pollutants, PM can originate from primary or secondary sources. Their concentration can increase up to levels likely to be harmful for health and environment. The effects of the particles on health and environment depends on the size, affecting both the lifetime and the physical and chemical characteristics. Particulate with diameter less or equal to 2.5 micrometers are the most harmful to human health as they can reach the deepest respiratory tracks. Different phenomenon contribute to particles characteristics and composition change. The condensation or evaporation of vapor species, the coagulation with other particles, the chemical reaction or the activation in the presence of water supersaturation to become fog and cloud droplets [9]. In this study, we

measured $PM_{2.5}$ as well as PM_{10}.

Ozone (O_3)

Ozone is a gas found in different part of the atmosphere. Depending on where it is located in the atmosphere, ozone can be useful or detrimental for leaving organisms. In the stratosphere, O_2 molecules dissociate to singles oxygen molecules (O) under sunlight. The O_2 will react with O to produce O_3. The O_3 atoms turn into O and O_2 under sunlight. These reactions are continuous which maintain stratospheric O_3 concentration. Although this cycle can be perturbed by anthropogenic emissions. Effort have been made to protect the stratospheric O_3. This ozone occurring naturally in the stratosphere and protecting life on earth from the sun's harmful rays is considered as good ozone. On the other hand, ozone formed in the lower atmosphere from chemical reactions of its precursors such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) under the presence of sunlight is considered as bad ozone. This ozone may damage plants and trigger health problems. Even at low levels, people with respiratory illnesses such as asthma are affected. Wind can carry ozone hundreds of miles from its source. Tropospheric ozone can be generated by the following reaction.

$$VOCs + NOx + CO \longrightarrow \xrightarrow{Sunlight} \longrightarrow O_3 + \text{Other products} \tag{1.1}$$

The interaction between primary pollutants such as volatile organic compounds (VOCs), nitrogen oxides (NOx) and carbon monoxide (CO) generate ozone and other products in the presence sunlight.

1.5 Scales of air pollution

From the 1950s to the beginning of the 21^{st} century, the sources and scales of air pollution along with it impacts have been recognized. Anthropogenic activities including industrial emission, combustion generated exhausted gas, smokes and dust from traffic and agricultural activities directly affect local air quality. Secondary pollutants from these emissions can significantly

engender consequences on health and environment beyond local level; on scales of hundreds to thousands of kilometers. Atmospheric studies have shown that up-drafted pollutants in high altitude can be transported by strong wind to other continents. Consequently, intercontinental transport of air pollutants can also have a major impact on local and regional air quality [29]. Atmospheric pollution is observed at three different scales depending on the pollution source, physical and chemical characteristics of the pollutants and, the weather condition. Namely; local level with a time scale of the order few hours to few days, regional level of the order of days , and global level with a time scale of the order of years.

The lifetime can strongly affect the scale of the pollution as it determines the pollutants transport under long distances. The more the pollutants stay in the atmosphere the more likely they can be transported under long distances by natural phenomenons; especially winds blowing. For instance, fine PM can be transported under long distances due to their light molecular weight. Locally produced pollutants can also undergo moderately complex photochemical reactions to originate the formation of secondary pollutants in the atmosphere. These pollutants (O_3 and its precursors for instance) can travel under long distances and have regional to global repercussion. On the other hand, when the lifetime of a pollutant is short, it will not be transported under long distances and therefore will have local repercussions.

1.6 Effects of air pollution

Atmospheric pollution highly affects our environment. Air pollutants change the natural environmental conditions including stratospheric ozone depletion, climate change, visibility reduction, crops lost, acid rain, haze, eutrophication. These result in biodiversity lost as well as health problem.

Hazardous air pollutants or toxic contaminants are any substances that may cause or contribute to an increase in mortality or serious illness [9]. A poor air quality has significant effects on human health. These are enhanced by health history, age and other factors. Sensitive people including those suffering from respiratory diseases, children and elderly are the most affected

by air pollution. Because children are closer to the ground, breath much quicker than adults and their bodies are developing, they are highly subject to the air pollution effects [12]. Compared with adults, children walking on busy roads may be exposed to up to a third more air pollution [30]. During the developmental stage, the exposure to air pollution can hinder lung growth, inhibit brain development and increase the risk of conditions such as asthma [31]. Different impacts of air pollution from different air pollutants are observed on human body as sown in Figure 1.3.

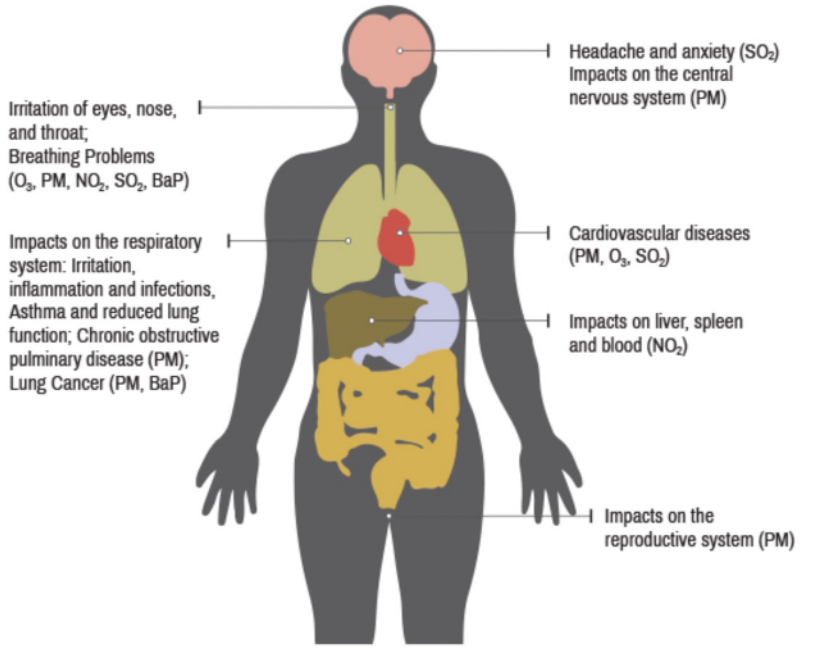


Figure 1.3: Health effect of air pollution (Adopted from [2])

1.7 Atmospheric pollution in West Africa

West Africa covers the entire western part of Sub-Saharan Africa (SSA). It covers approximately 16 countries including Mali, the interest of this research. SSA had one of the lowest populations in 1950s but, experiences a very rapid grow from then. The projection shows a continual exponential growth for this region while the other regions show either a constant trend like Europe and North America or a decreasing trend like Central Asia and South Asia (Figure 1.4).

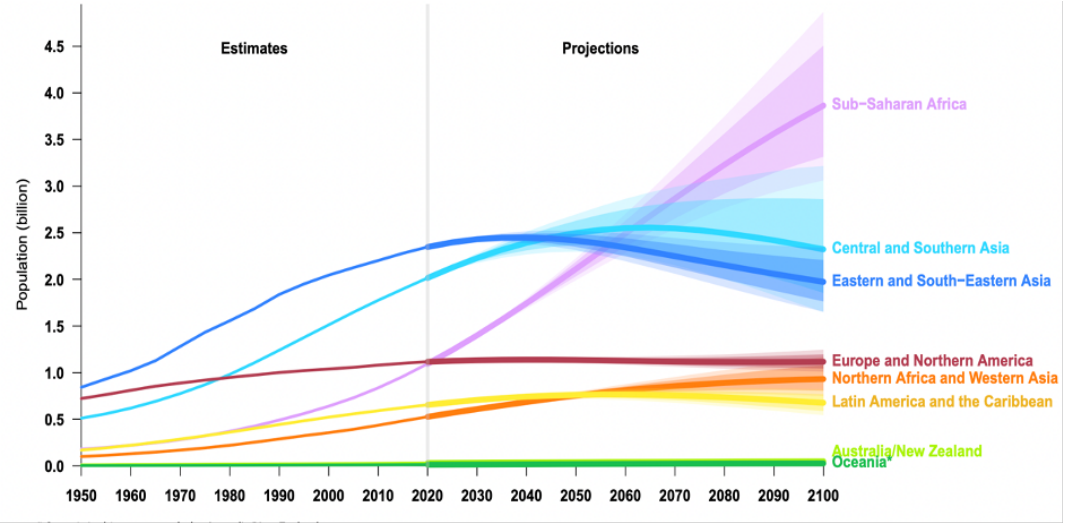


Figure 1.4: Population growth by SDG region: estimates, 1950-2020 projections and 2020-2100 percent prediction [3]

West Africa has an area of approximately 6.14 million km^2, equivalent to one fifth of the African continent [32]. Its population rose from around 40 millions of inhabitants in 1930 to 85 million in 1960. In 2003, SSA represented nearly 4.6% of the world's population (290 million of inhabitants), 43% of that of Sub-Saharan Africa, 60% of that of the European Union, about the same as that of the United States, 2.2 times that of Japan and 9 times that of Canada [33] [34].

West Africa has experienced a high increase in population density in the last 20 year [35]. It is therefore not surprising that West Africa has experienced an extraordinary urbanization in the last few decades. This explosive population growth together with urbanization have put the environment in West Africa under a lot of stress and raised a number of crucial issues such as the increase in poverty and the deterioration in the living standard of the populations in recent years [36] [32]. The main issues are centered on traffic, biomass burning and waste management system.

Traffic. As urban cities grow, traffic volume increases and so does traffic pollutants emission. The increase in transportation demand, the bad condition of the roads associated to the characteristics of vehicle fleet and the quality of the fuel used in traffic lead to a high traffic

emission level [37] [38]. The lack of means and infrastructure in this region, often leads to anarchy in the population daily life such as the traffic sector. In fact, air pollution in West Africa have reached a very alarming level as it is being felt by the local populations. Local inhabitant from west Africa (Cotonou and Ivory coast) have reported that air quality is very uncomfortable for breathing especially for sensitive people. Johannes, a journalist in Cotonou, capital of Benin who sufferers from asthma reported that inhaling exhaust fumes while waiting at a traffic light for a few minutes usually triggers his asthma attacks [39].

Cooking. In Africa around 3 billion people cook and heat their homes using open fires and simple stoves burning biomass (wood, charcoal, animal dung and crop waste) [40]. In West African cities, the main fuel used for cooking and heating is wood and charcoal. Observed pollutants' concentrations are often a lot higher than the WHO recommended limits.

Waste incineration. Waste combustion in West African cities emit considerable number of polluting chemicals. The sorting waste system is almost in-existent and the collection system is underdeveloped. In Mali as in other African counties, private individuals collect households' wastes using private cart as personal businesses. There are very few formal companies in charge of the collect. The collected wastes are dumped at uncontrolled and inadequate waste disposals sites. These accumulate to huge waste piles which are later subjects to open and uncontrolled incineration. Outdoor incineration is the main ways of waste management.

Chapter 2

Instrumentation and methods

2.1 Study area description

2.1.1 Characteristic of Bamako city

The study area (Figure 2.1), Bamako city is the administrative, political and economic capital of Mali, a landlocked West North African country. Mali has an area of 1,241,238 square kilometers and 20 933 072 inhabitants in 2020. It borders Algeria in the North, Niger in the east, Burkina Faso and Ivory Coast in the South, Guinea in the Southwest and Senegal and Mauritania in the West. This geographical location offers Mali an enormous economic potential because of the easy access from the surrounding countries. On the other hand, it exposes the country to all forms of migration from within and outside the country. Inhabitants from the neighboring countries commute for trade, businesses and job seeking. This migration is more pronounced in Bamako as it contains most of the infrastructures, offices and industrial units. Thus, the city of Bamako astronomically located in the Southwest of Mali (12°39'0.00" N - 8°00'0.00" W) with an area of 267 square kilometers and a population of about 3 million in 2021 [41] [42] is the most populated and most industrialized city among the 10 regional capitals.

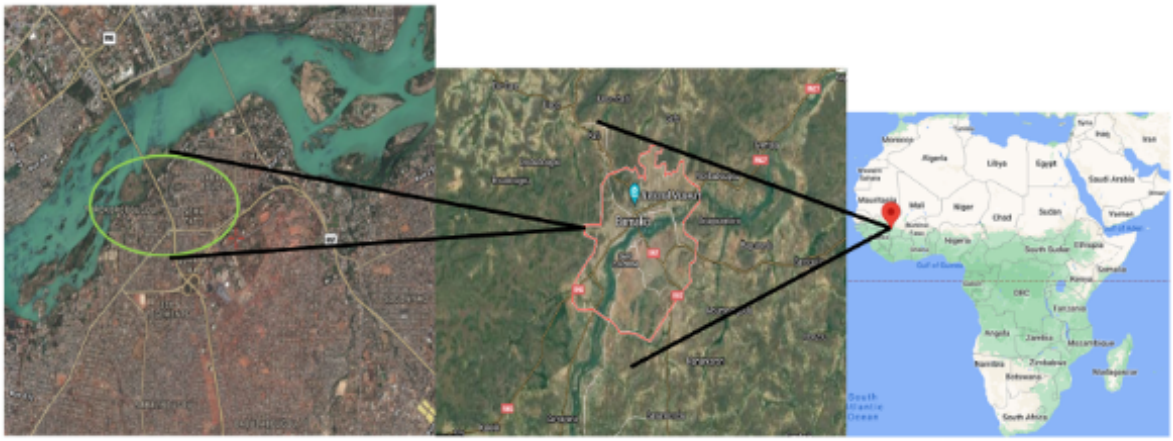


Figure 2.1: Location of study site; The Urban city of Bamako in Mali

Major pollution sources in Bamako city

Bamako is an urban city undergoing environmental pollution from diverse anthropogenic activities as well as natural processes. The major possible pollution sources in this region are likely related to traffic (dust resuspension, chemicals generated by the second-hand cars

and several thousands of motorbikes) waste incineration, household activities (such as biomass combustion), agricultural activities and, industrial activities. In addition to these anthropogenic sources, natural dust transported by a hot and dry wind blowing from the East and Northeast of Mali (Sahara Desert) towards Western Sahara could transport particulate matter (PM). This wind called harmattan is strongest in the late fall and winter (from late November to mid-March). Furthermore, the geographical situation of Bamako; city surrounded by hills, doesn't allow the air to circulate well. As a result, the air is stagnant and polluted in Bamako.

2.1.2 Sampling sites descriptions

In this study, air pollutants were sampled at different locations in the city of Bamako. PM was sampled in Bamako's inhabitants living in different neighbourhoods. Furthermore, sampling were carried at specific emission sources. These included PM samplings on filters and, the major air pollutants sampling at a typical roadside. When selecting sampling sites, we considered the emission sources and the availability of energy supply. Bellow, a brief description of each sampling site.

Domestic sampling site

PM emitted from cooking, the use of insecticides (IST) and incense (ICS) were collected on filter at a residential area; the neighborhood of ATT Bougou (12°61'15.5"N 7°99'64.1"W). The sampling site was mostly characterized by anthropogenic activities. The neighborhood mostly used sheltered houses, small private schools, small businesses and shops. Samplings were conducted in households (kitchens and living rooms).

Road side sampling site

Emission from traffic were collected at a typical traffic site in Bamako city. The selected site belongs to Bako djikoroni neighborhood (12°34'59.6"N 8°01'22.8"W). Samples were collected on filters at the second floor of a building at 3.80 meters from the ground. The sampling site was affected by diverse anthropogenic activities. The building was located at a cross road next to a gas station. The site was characterized by an intense road traffic with high occurrence of traffic

jams especially during rush hours. The vehicle fleet was mainly characterized by, 2 wheels (motorcycles, moto taxis), 3 wheels (moto taxis with 3 wheels), 4 wheels or more (personal cars, taxis, SOTRAMA, trucks). These vehicles were predominantly old and damaged. Furthermore, anthropogenic activities such as uncontrolled incineration, street food preparation, construction activities, and animal husbandry were common in Bamako city.

Air pollutants sampling site

The sampling site for major the air pollutants was located in ACI 2000 neighborhood at 12°38'15.2"N 8°02'17.6"W. This site was one of the Malian meteorological agency stations. The data were collected from February 2021 to August 2021. Similarly to the sampling site on filters was characterized by a heavy road traffic. Besides, there was a restaurant that used charcoal at 50 meters South from the station. The site was characterized not only by traffic but also anthropogenic activities.

Asian Center for Air Pollution research (ACAP)

In addition to the samplings in the urban city of Bamako, samplings were performed at the ACAP laboratory in Niigata, Japan (37°50'44.2"N 138°56'32.3"E). Burning emissions from ICS and from different brands of IST (mosquito coils) from Mali and Japan were sampled on filters for comparison purposes.

2.2 Instruments

The main purpose of the samplings were to: (1) to determine the personal exposure to $PM_{2.5}$, (2) to characterize the chemical composition of PM emitted from different anthropogenic activities, (3) to assess the possible health risks from the exposure to these PM and,(4) to determine the behavior and variation the principal pollutants in the ambient air.

The first step of our methodology was to get partnerships with local institutions and agencies to support us during the samplings. Considering the distance between Japan and Mali, a constant communication was necessary during the sampling period. The laboratory of Atmospheric

chemistry of Kyoto University, Japan collaborated with the laboratory of molecular biology of Bamako University, Mali and the Meteorological agency of Mali (Météo-Mali). Details about sampling procedure, written and visual support were elaborate and sent the collaborators along with the equipments prior the samplings.

Personal exposure to $PM_{2.5}$ measurement

Palm size optical $PM_{2.5}$ sensors

Palm size optical $PM_{2.5}$ sensors were used to determine personal exposure level to $PM_{2.5}$ generated from diverse anthropogenic activities. The experimental setup is shown in Figure 2.2.

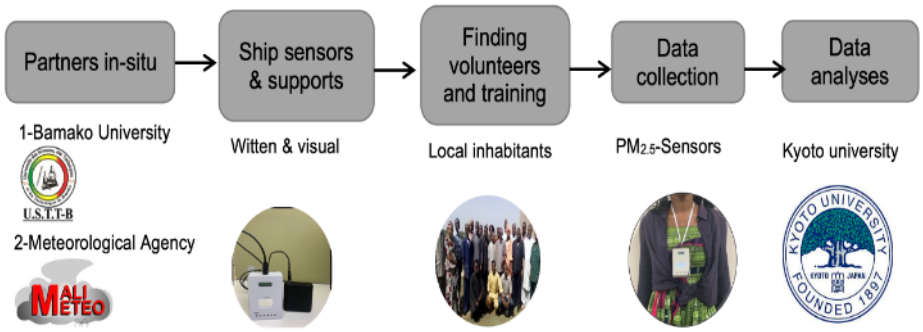


Figure 2.2: Experimental setup of the personal exposure to $PM_{2.5}$ measurement

Each participant wore a palm-sized optical $PM_{2.5}$-Sensor. The palm-sized sensor was developed and evaluated by Japanese researchers from the Institute for Space-Earth Environmental Research, Nagoya University in collaboration with Eco Solutions Company. $PM_{2.5}$-Sensor was specifically designed to give the mass concentration (in $\mu g/m^3$) of PMs of 2.5 microns or less in diameter. The sensor is portable, light, inexpressive, has a low energy consumption, a good data storage capacity, and is reliable. The size is 52 mm $\times$ 45 mm $\times$ 22 mm (Figure 2.3a) including a printed circuit board with a connection port for data processing and a power supply [43].

The sensor can store data for up to 30 days approximately in a frequency of one data set per minute and up to 3 months in a frequency of one data set per 15 minutes. The collected data is saved in the device and can be downloaded by connecting it to a computer on which the $PM_{2.5}$-Sensor software is installed. The recording frequency can be modified in the software's

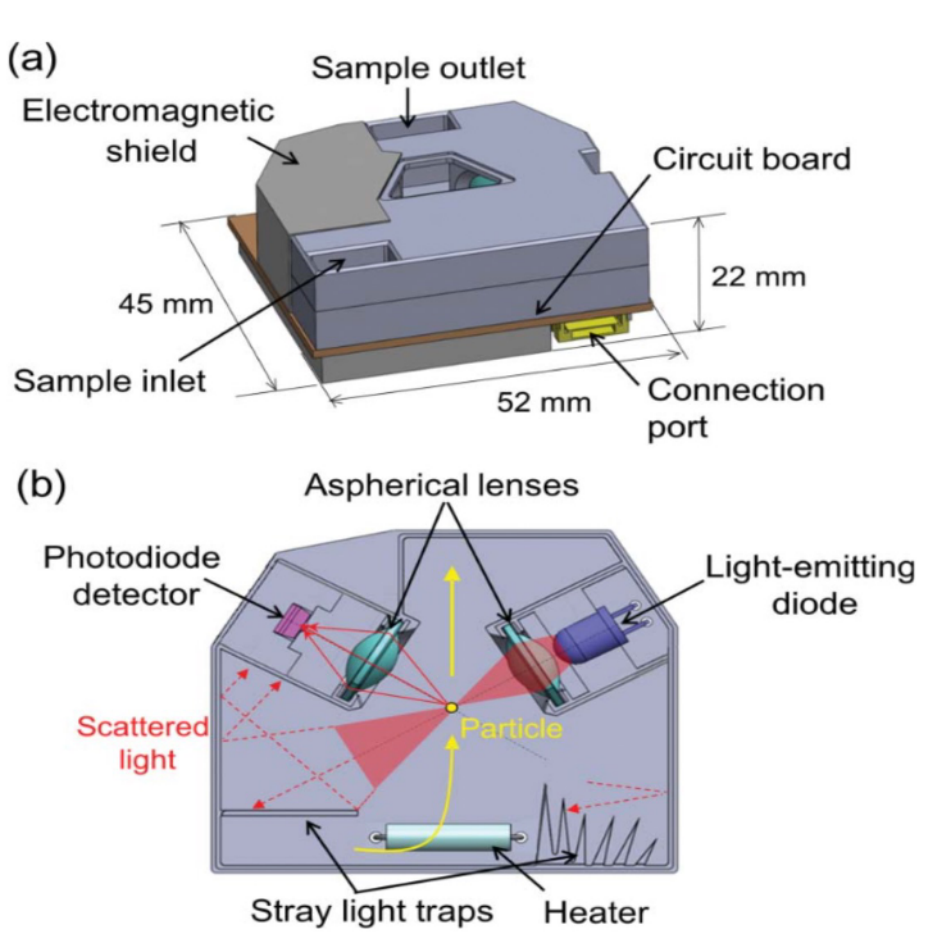


Figure 2.3: Figure. Schematic diagram of $PM_{2.5}$ sensor; (a) outside (b) inside

setting. $PM_{2.5}$-Sensor works on the principle of heat convection transfer and light scattering of the particles inside the instrument (Figure 2.3b). It is a mode of heat transfer by the mass motion of a fluid such as air. Convective heat transfer occurs when the surface temperature of a heated object differs from that of surrounding fluid and moves energy away from the source of heat [44]. Light scattering of particles takes place when particles are irradiated with a source of light which is a laser in the case of $PM_{2.5}$-Sensor. The change of the light direction from the laser after it hits the particles is called light scattering. Figure2.3b shows the heater up-drafting particles entering the instrument. These particles are directed towards the light emitted by the light emitting diode (λ = 625 nm) where; they are irradiated. The aspherical lenses focus the emitted and scattered lights by both; the light emitting diode and the particles. The photodiode detector detects the scattered light from the irradiated particles. Weaker scattered lights from smaller particles are detected by the stray light traps. The light scattering intensities are proportional to the sizes. The concentration of particles is estimated from the distribution of light

scattering intensity from single particles and the real time $PM_{2.5}$ mass can be read on the digital screen of the sensor. According to the specifications, $PM_{2.5}$-Sensor is optimized to measure particle over 10 $\mu g/m^3$, therefore, the values less than 10 $\mu g/m^3$ would be less reliable.

Reliability test of portable $PM_{2.5}$-Sensor

Performance of the sensor was tested by comparing it with an optical particle counter (OPC, GRIMM, 1.109). The samplings were conducted at Kyoto University, Yoshida South Campus West wing from December 1^{st} to 22^{nd} and from January 7^{th} to February 20^{th}. Figure 2.4 shows the sampling site located at the third floor of the building.

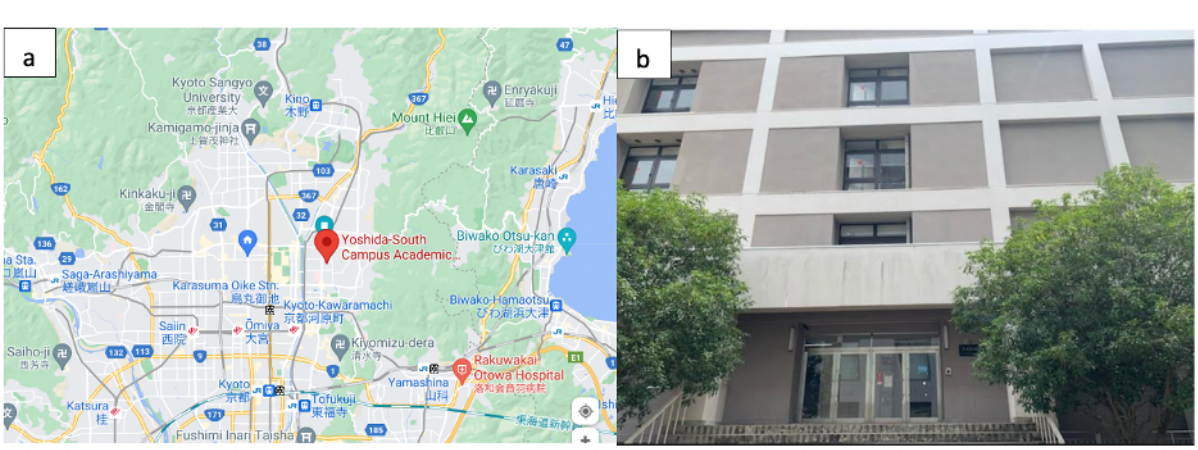


Figure 2.4: Yoshida South campus information. (a) Location of the sampling site. (b) Image of the building

GRIMM covers the range from 0.25 to 35 micrometers or more depending on the settings and the model's speciation. To compare the instruments outputs, we considered only the $PM_{2.5}$ fraction from GRIMM-OPC. As GRIMM provides the particles concentration by size range, we could select the fraction we needed for the comparison. Particle number distribution over 250 nm in diameter by OPC covers over 80% of the volume fraction and was converted into mass concentration using the typical mass density of ambient particles of 1.2 g cm^{-3} [45] [46]. The results showed a good correlation between the two instruments: R= 0.90 for 24h average and R= 0.82 for 1 hour average (Figure 2.5a and b). Furthermore, the $PM_{2.5}$-Sensor data and the GRIMM-OPC data showed an agreement in the time variations (Figure 2.6a).

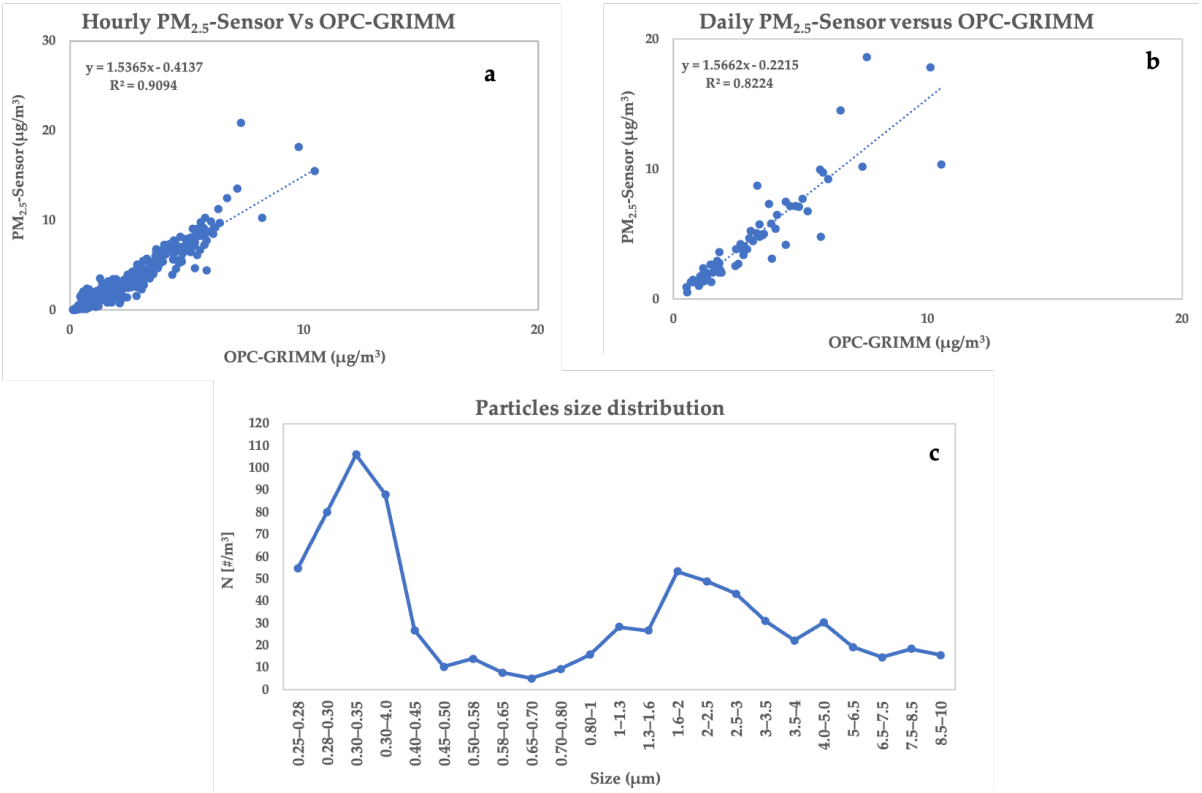


Figure 2.5: (a) Correlation plots of the $PM_{2.5}$-Sensor versus the GRIMM OPC from December 1–22, 2020, and from January 7 to February 20, 2021; hourly average concentration.(b) Correlation plots of the $PM_{2.5}$-Sensor versus GRIMM-OPC from 16 November to 22 December 2020, and from 7 January to 20 February 2021; daily average concentration. (c) Typical size distribution of PM from the GRIMM OPC Daily variation of $PM_{2.5}$

$PM_{2.5}$ gives the mass concentration of particles in the unit of $\mu g/m^3$ and OPC-GRIMM in number of particles per litter (N/L). We converted the output of the OPC-GRIMM from N/L to $\mu g/m^3$ using equation 2.1 before proceeding to the comparison.

$$M = VN\rho \tag{2.1}$$

Where; V is the volume, N: Number of particles per liter and, ρ:Density.

Additionally, data obtained from the Japanese Ministry of Environment's website (AEROS) available at (http://soramame.taiki.go.jp/) were used for comparison. The results showed a good agreement in time variation between Yamashina station (located at 5.8 km from Kyoto University, Yoshida South Campus) and $PM_{2.5}$-Sensor from November 16^{th} to February 20^{th} (Figure 2.6b).

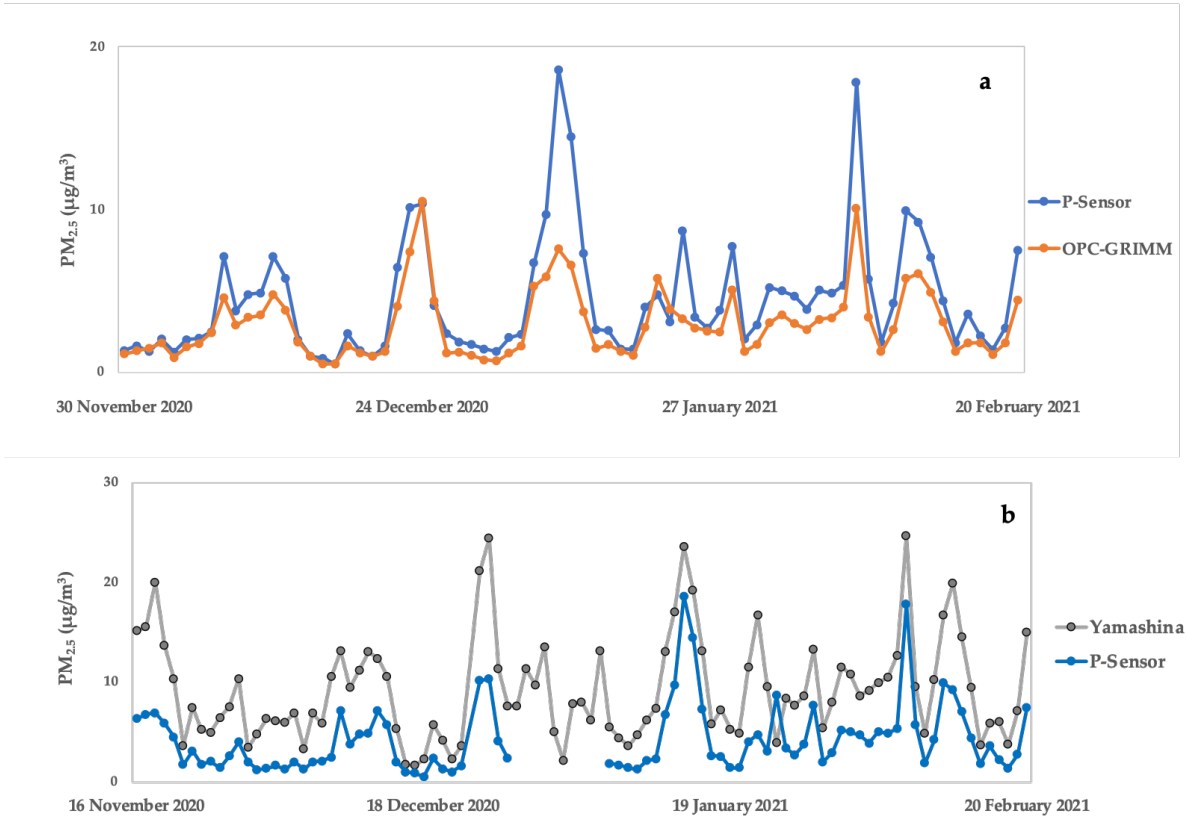


Figure 2.6: Daily mass concentration variation: (a) concentration for the GRIMM-OPC versus the $PM_{2.5}$-Sensor, (b) concentration of the $PM_{2.5}$ for the Yamashina versus $PM_{2.5}$-Sensor. P-Sensor: $PM_{2.5}$-Sensor

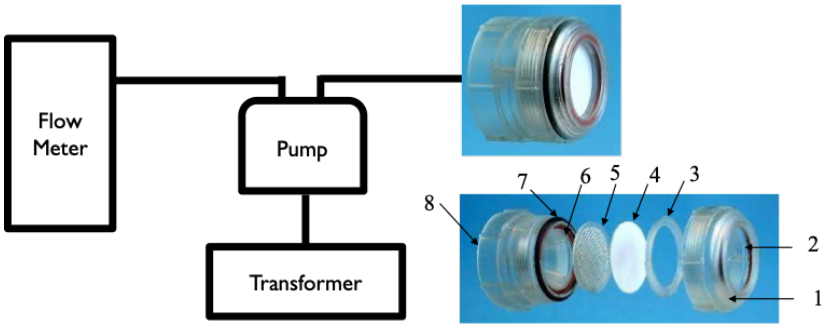
Chemical composition analysis

$PM_{2.5}$ are diverse in characteristics including the chemical composition which has been linked to health issues in countless previous researches. Various metallic components commonly detected in PM from urban areas were identified as harmful to human health. Carbonaceous have adverse effect on health. Furthermore, acidic ions can cause harm to human and environment. The chemical composition is also important for the source apportionment of particulate. Thus, it was necessary to investigate the chemical composition. PM were collected on filters at specific emission sources in Bamako city for the chemical composition analysis. Additionally, the indoor samplings were implemented in Japan at the ACAP to get firther information on the composition of the PM emitted from IST and ICS and, to compare different insecticide and incense products. The main goals of the chemical composition analysis were to

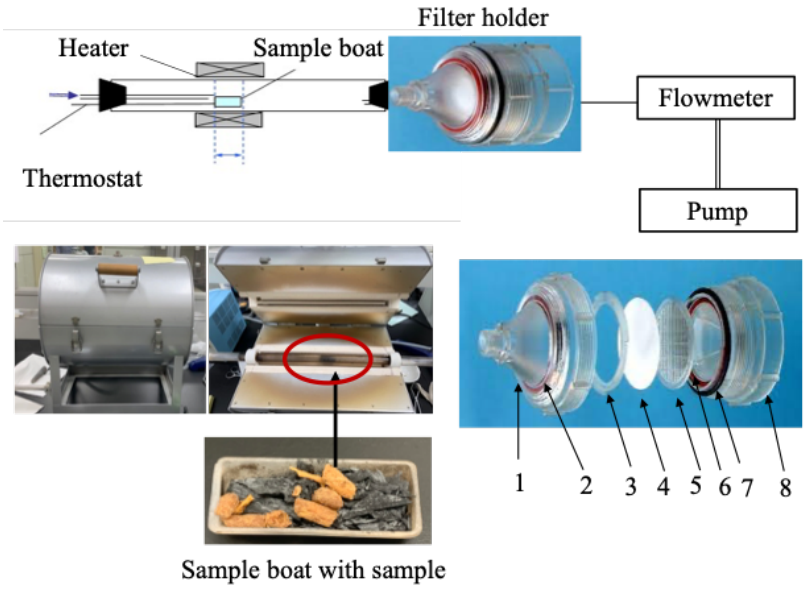
determine the source contribution of ambient PM, quantify the different components of PM for specific emission sources and, have a deeper insight on the exposure risks.

Filter sampling systems

The chemical compositions of the PM were determined by analyzing samples collected on 47 mm in diameter Teflon and quartz filters. We had two filter pack sampling systems (Nilu filter holder). This system was designed for particles and gaseous compounds sampling. The filter holders were designed for 47 mm diameter filters [47]. Several devices were used as part of the filter pack systems. Figure 2.7a shows a schematic description of the filter pack system used in Bamako and Figure 2.7b the one used at the ACAP.



(a) Bamako city sampling



(b) ACAP samplings

Figure 2.7: Filter pack systems in Bamako city and the ACAP laboratory

Nomenclature for Figure 2.7a and Figure 2.7ba and b: (1) Inlet, (2 and 6) Silicone O-rings (red), (3) Champing ring, (4) Quartz or PTFE filter, (5) Filter backing, (7) Nitrile O-ring (black), (8) Outlet section. The difference in the Nilu filter holder system for both setting result in the type of inlet. An open face inlet for Figure 2.7a and an inline inlet for Figure 2.7b [47].

Ambient air pollutants measurement

AQT400 ambient air monitor

Major air pollutants were collected by the meteorological agency of Mali. The air quality transmitter Vaisala series AQT400 (Figure A.2) was used to collecte data on the criteria ambient air pollutants. Vaisala AQT400 is specifically designed for air quality monitoring in urban areas such as traffic and industrial sites. It measures ambient air contents of diverse pollutants. It includes gas sensors for (CO, NO_2, SO_2, O_3) and a laser particle counter $PM_{2.5}$ and PM_{10} measurements.

2.3 Sampling procedure

Personal exposure to $PPM_{2.5}$

Personal exposure to $PM_{2.5}$ was measured in participants who lived in Bamako from September 2020 to February 2021 (Figure 2.8). The participants were selected based on major occupations in the city: office workers (OW), drivers (DRI), cooks (COOK), and students (ST). Participants in these occupations were selected with no restrictions on gender, age, area of residence, house conditions, and personal habits (smoking, exercising, etc.). They were from 12 to over 60 years old.

Each participant provided personal information after agreeing to take part in the research. For each occupational group, at least three participants were sampled for 3 days. The sensor was worn around the neck on the chest, close to the breathing zone (Figure 2.9b). The real time mass concentration of $PM_{2.5}$ were recorded in 5 seconds intervals.

The sensor was removed during bathing and sleep. At those times, it was placed on a sup-

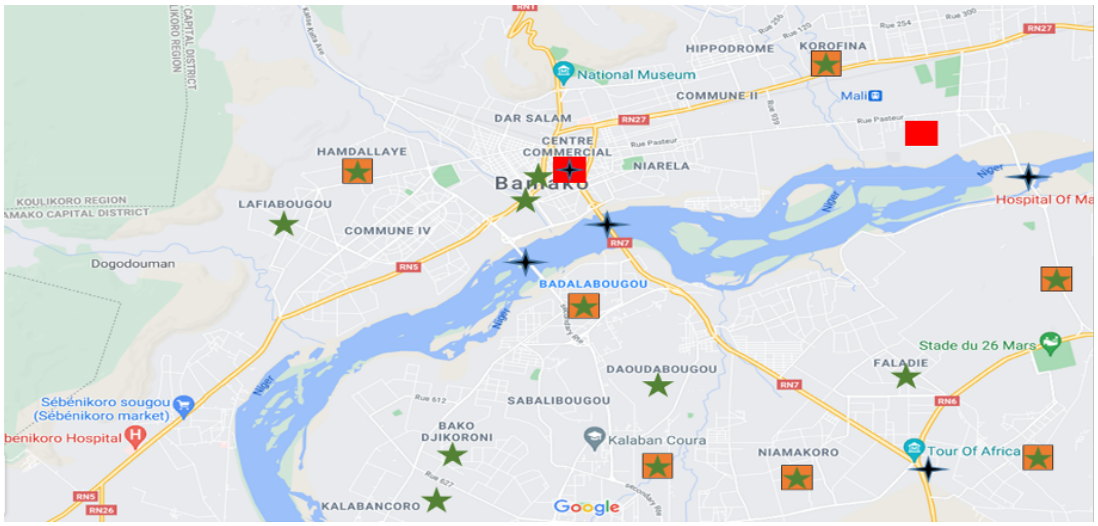


Figure 2.8: Different microenvironments' locations of the participants on Google Maps; green star (houses), orange square (work places), black star (high traffic areas), red square (industrial zones)

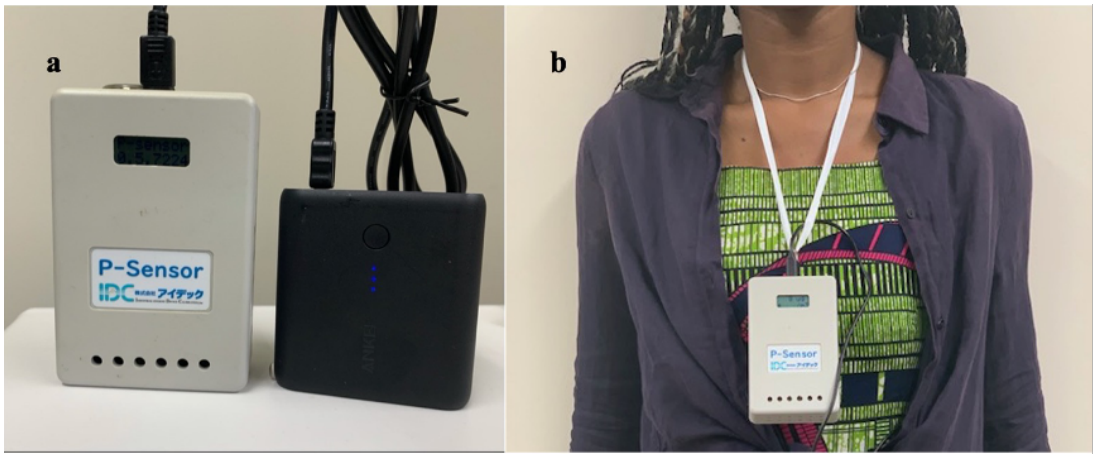


Figure 2.9: $PM_{2.5}$-Sensor (a) and its typical orientation (b)

port located in the same microenvironment. Each participant recorded their daily activities and microenvironments in a diary during the sampling period. They gave notice whenever they switched their microenvironments or activities. The diaries provided information on the time, location, and activities of the participants for 72 h. The time and location were characterized by different activities and microenvironments indoors (such as home, home with incense and insecticides, workplace, classroom, other activities) and outdoors (such as market, cooking, driving, other activities). $PM_{2.5}$ exposure data for a participant's total exposure were then obtained from measurements in various locations during the sampling period. The participants' information

(occupation, gender, age, mean of transportation, and personal habits) were collected using Table A.2

Participants' questionnaire and diaries

Our participants were asked to fill out a questionnaire in order to get their basic personal information (age, gender, occupation, mean of transportation and personal habits). We considered the information in our data analyses to have a better understanding on the exposure to particles (TableA.2). Participants also holed a diary specifying their activities while carrying the samplings. Each participant gave detailed information on their time, location and activities during the sampling period. The information was used to determine the level of exposure to particles during different activities in different microenvironments.

Ambient air pollutants

For the ambient air pollutants measurements, no particular sampling procedure was needed. The AQT400 was installed by its Manufacturing company. After installation, the instrument automatically collect data on specific pollutants depending on the instrument speciations. In the present study, Carbone monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), PMs 10 microns or less in diameter (PM_{10}), and 2.5 microns or less in diameter ($PM_{2.5}$) were sampled at a typical traffic site in Bamako city.

Sampling procedure for chemical composition analysis

- *Samplings in Bamako city*

The purpose of the samplings in Bamako city was to gather information on the PM emitted in the real-life conditions. We carried sampling at specific emission sources identified as the main exposure sources after investigating the personal exposure. Figure 2.10 shows the sampling locations.

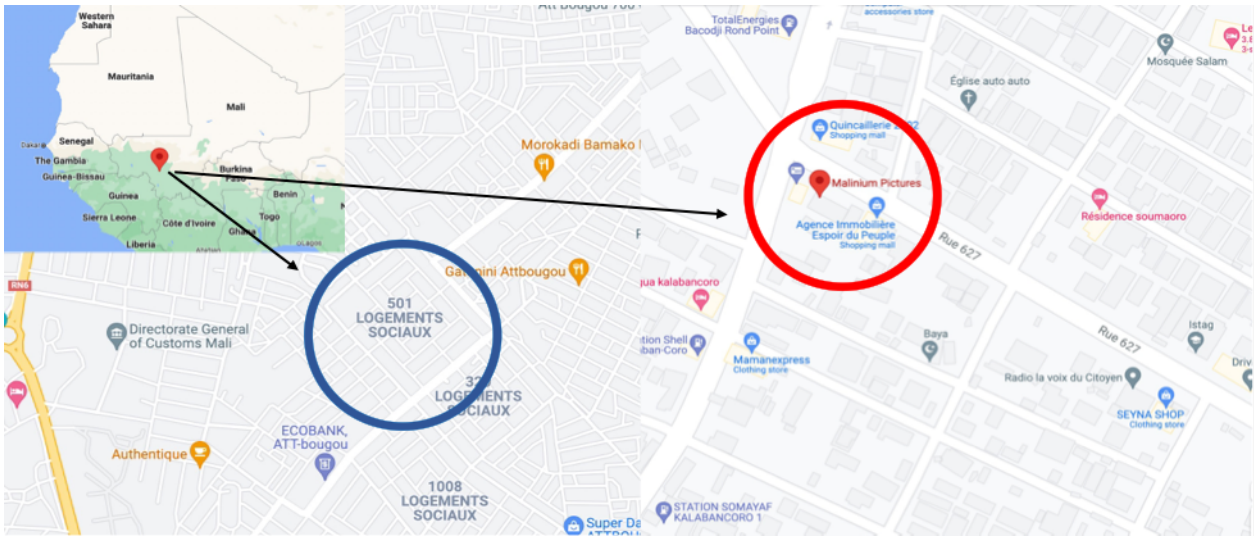


Figure 2.10: Sampling locations; Blue circle (residential area), red circle (typical traffic site Bamako city)

Incense and insecticide samplings were conducted in households living rooms (12.4 m^2). The samples were collected at a distance of 0.30 to 0.50 meter (Figure 2.11a) from the emission sources.

Figure 2.11: Sampling images in Bamako. (a) incense and insecticide combustion sampling. (b) Cooking period sampling

The samplings for the cooking activities were performed in the kitchens (semi-open). In Mali like many other countries in the Western Sub-Saharan Africa, the kitchen is located in the house yard. The cooking space is generally in an open area or in a semi-open kitchen. The filter pack system was placed at a distance of 0.8 to 1 meters from the cooking stove. The distance

between the cook and the cooking stove was approximately 0.5 to 0.7 meters (Figure 2.11b). For the traffic sector, PM were collected at the second floor of the Malinum building; 3.80 meters from the ground (Figure 2.12a and 2.12b).

Figure 2.12: Sampling images in Bamako city. (a) Sampling site building, (b) Filter pack, (c) View from the building. Image (a) and (c).
© Malinium Pictures

All samples were collected at a flow rate of 9L/mn and the sampling time was proportional to the duration of the activity. The duration of the cooking activity, from fire ignition was between 1h30 mn to 3h. IST and ICS products were sampled for 2h. For the roadside PM collection, the duration of each samplings was for 24h. $PM_{2.5}$-Sensor was placed in the same microenvironment to simultaneously measure the $PM_{2.5}$ mass concentration.

- *Laboratory samplings (ACAP)*

Samplings at the ACAP laboratoryin Niigata, Japan were performed to provide more information on the chemical composition of IST and ICS and to compare different IST and ICS products from Mali and Japan. The burning emission from various ICS and IST (mosquito coils) brands were sampled to evaluate the difference in chemical composition for the different products. The controlled experiments were conducted in a closed setting using a ceramic heater (ARF1, Heat Tech Co., Japan) directly connected to the filter pack system. The samples were place in a sample boat and introduced in the tubular zone of the heater for combustion (Figure 2.7b).

2.4 Quality control and quality assurance (QC/QA)

- **Personal exposure to $PM_{2.5}$**

The palm-sized $PM_{2.5}$ was evaluated by its developers using two types of standard beta attenuation monitors (DKK-TOA, model FPM-377 and Kimoto, model PM-712) at four different locations in Japan (Fukuoka, Kadoma, Kasugai, and Tokyo). The daily averaged mass concentration obtained from the $PM_{2.5}$ sensors were in good agreement with the standard instruments (with R between 0.89 to 0.95). Our results from the comparison study (GRIMM-OPC Vs $PM_{2.5}$-Sensor was in line with the results obtained by Nakayama et al in 2018 [43].

To ensure the quality of the data collected on personal exposure to $PM_{2.5}$, the participants were given lectures to explain to them the content of the study, as well as its objectives and methods prior to the data collection. They were instructed on how to record detailed information during the sampling period. The lecture also included demonstrations on how to operate the sensors. Each participant was given a chance to operate a sensor before the official start of the samplings. The communication between the participants and the research team was constant during the sampling period so that any problem or question could immediately be addressed. The batteries were regularly charged during sleep time without interrupting the samplings, to prepare for the next day. This was possible, as the batteries have multiple connection ports.

Data were downloaded and saved from the sensors after each participant completed the required sampling period. The sensors and batteries were checked for any malfunction before assigning them to the next participants. Only data obtained from participants providing clear information on time, location, and activity were used for the data analysis.

- **Chemical composition analysis of PM**

Cleanness plays a critical role in the accuracy of the chemical analysis. To minimized samples contamination, all the filter handling process was performed wearing gloves. The sampling materials were sterilized before and after each sample preparation and collection. In addition to the samples collected at the different emission sources, four travel blank filters were collected; quartz and polytetrafluoroethylene (PTFE) filters to be able determine any possible contamination occurring in situ or during the transportation. The collected samples as well as travel blanks were tagged, place in plastic boxes then zip logs (Figure2.13). Samples were stored in a refrigerator at 4 ± 1°C before being shipping and before analysis.

Figure 2.13: Collected filter samples in tagged plastic boxes and zip logs

To ensure that the analytical laboratory instruments and procedure were effective, the ACAP regularly performs instruments checks and calibrations following the Acid Deposition Monitoring Network in East Asia (EANET) quality and control assurance procedures. Standard samples with different dilution concentrations were tested by ion chromatography for anions and cations analysis. To evaluate the analytical protocol for metallic elements, the values from measured elements were compared to the ones of the Certified Reference Material (CRM). The analytical results were in a good agreement with the certified reference values within analytical error [48] [45]. After analysis, the values obtained from the blank filters were subtracted from the

value obtained from the collected filter samples for data analysis. The values under the detection limit were considered as not detected (nd).

2.5 Data analysis

For data analysis and graphic representations. We used Excel version 16.57, Chemical mass balance (CMB8J ver 3.1) and Principal component analysis method (PCA) with XLstat. More detail on CMB and PCA method is provided in the next section.

For the personal exposure and the criteria air pollutants, the data collected from the devices (in situ) were directly used for calculation while for the chemical analysis of PM, collected filter were analysed at the ACAP laboratory before calculations.

2.5.1 Personal exposure

The diaries and the recorded concentrations from the devices were used to calculate the personal exposure to $PM_{2.5}$. Background concentrations were considered as concentrations recorded in the absence of local emission sources. These concentrations were very low compared to those recorded during the participants daily activities and were included in our calculations.

Personal exposure calculation method: case of the office workers

The personal exposure for a participant $PM_{2.5}$ exposure was calculated using the recorded concentrations for different activities and microenvironments along with the time spent for these activities and microenvironments.

$$OW1d_1 = \frac{\sum_{i=1}^{n} OW1C_i t_i}{24} \tag{2.2}$$

Where; $OW1d_1$ is the average exposure of office worker 1 for day 1. $C_i t_i$ represents the integrated exposure concentration of office worker in one day. It is obtained from the product of

the total average concentration recorded in all the microenvironments on day 1; such as home, office, transportation and stores (μg/m^3) and, the time spent in the microenvironments (hours). 24 is one day in hours.

Average exposure of all the office workers (as a group) would be calculated as followed;

$$AvgOW = \frac{OW1d_1 + OW1d_2 + OW1d_3 + .. + OW2d_1 + OW2d_2 + .. + OWnd_3}{N} \tag{2.3}$$

Where; OW is the group of office workers, OWn represents to the total number of office workers. d_1, d_2, d_3 are sampling days 1, 2 and 3. N is the number of office workers multiplied by the number of sampling days.

The same method was applied to obtain the exposure concentrations for the group of students, cooks and drivers.

2.5.2 Ambient air pollutants

The ATQ400 directly provides air pollutants concentration in ppm for CO, SO_2, NO_2,O_3 and in μg/m^3 for PM_{10} and $PM_{2.5}$. The collected data were analyzed at Kyoto university to assess the ambient air quality at a representative road side in Bamako city.

2.5.3 Chemical composition analysis

For the chemical composition analysis unlike the $PM_{2.5}$ personal exposure and the ambient air pollutants measurement, the collected samples required further handling at the ACAP laboratory. Filter samples were prepared and analysed using different instruments for different constituents measurement. In this section, the analytical methods were described before the calculation methods.

- **Ion chromatography**

The Thermo Scientific Dionex TM ICS Model 2100 and DionexTM ICS1100 were used to identify the anions and cations respectively. Ion chromatography system operates using suppressed and non-suppressed conductivity detection to analyze ions. A common ion chromatography system includes six different stages; a liquid eluent, a sample injector, a guard column, a separator column, a chemical suppressor, a conductivity detector and a data collection system (Figure 2.14).

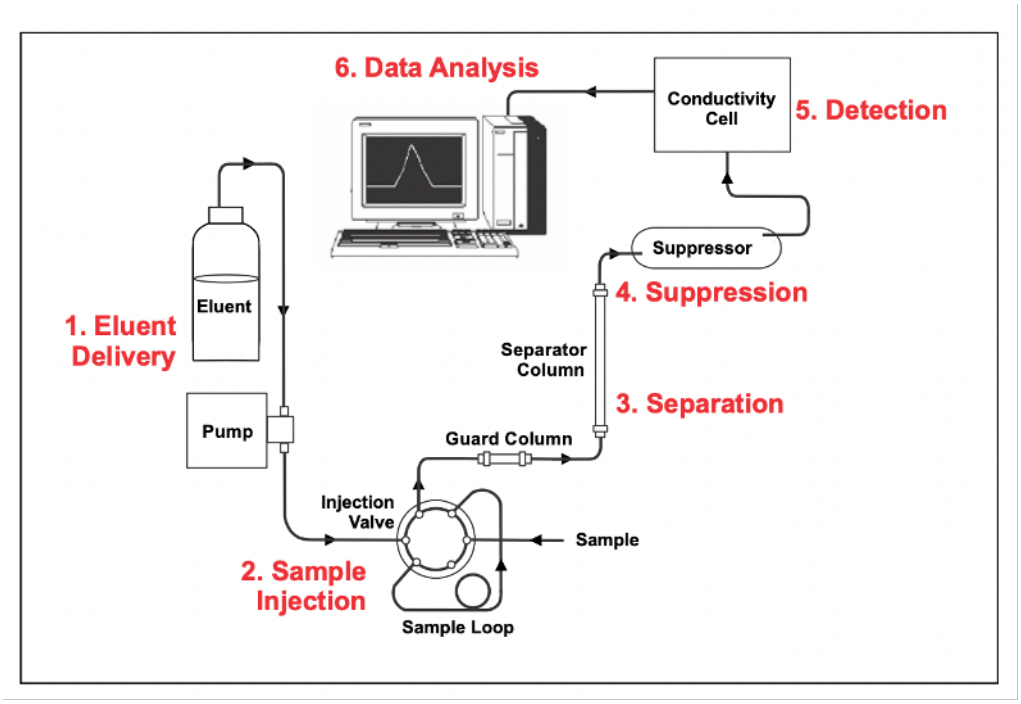


Figure 2.14: Ion analysis process (Adopted from [4])

Figure 2.14 shows the (1) Eluent delivery: the eluent's function is to carry the sample into the ion chromatography system and separate the ions. (2) The sample injection: The sample is automatically injected by an automated sampler from sampling tubes placed in the injection valve (Figure 2.15f). (3) Separation: before the sample goes into the separator column, the guard column removes any contaminant that might damage the separator column. In the separator column, the ions will be separated based on their interaction between these ions and the column. The stronger the interaction (the affinity of the ions with the column), the longer the interaction time (retention time). (4) Suppression: in the suppression stage, the suppressor suppresses the eluent conductivity and increases the ions detection. (5) Detection: As they

emerge from the suppressor, the conductivity cell will measure ions electrical conductance and produce signals based on their chemical or physical properties. The conductance is proportional to the concentration of ions. (6) Data analysis: The conductivity cell transmits the signals to the collection system. The software Chromeleon qualitatively identified and classify ions by comparing the signals produced by the samples to those produced by the standards solutions [4]

Sample preparation

For the ionic component measurement, both quartz and PTFE filter samples were sectioned using ceramic scissors. Half or one fourth of the filters were treated with 20 mL of distilled water. Tap water was purified using Milli-Q instrument (Figure 2.15c).

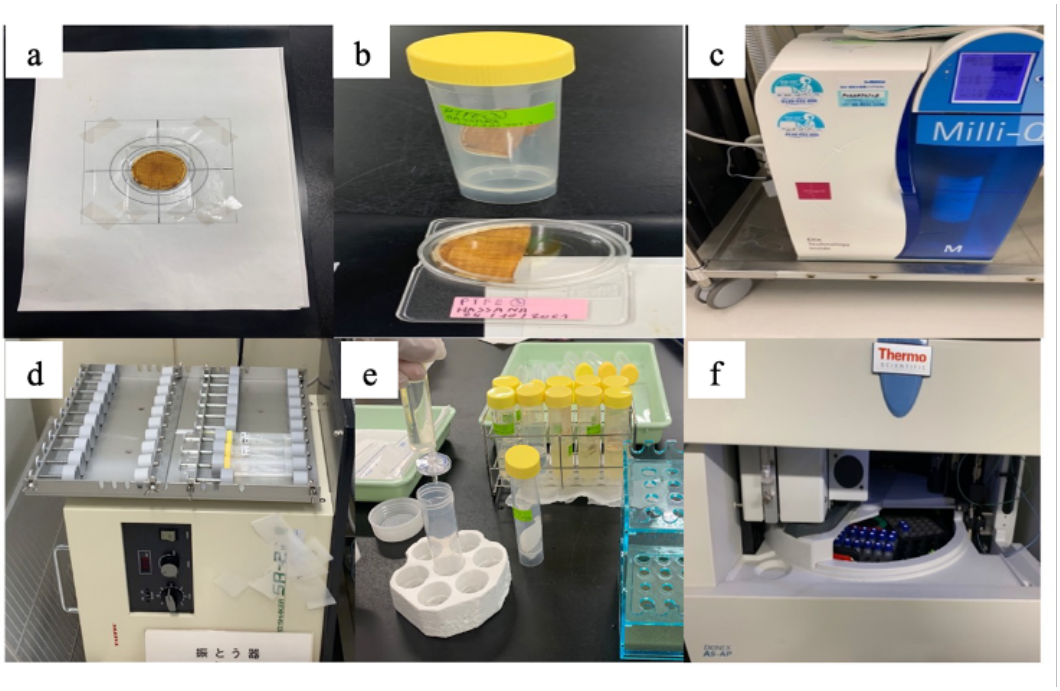


Figure 2.15: Sample preparation process for ion analysis. (a) Filter samples cutting board, (b) Filter sample for dilution, (c) Water purification system, (d) Extraction using an electric shaker, (e) Filtration using sterilized syringe and filter, (f) Sample injection valve with analysis tubes

For PTFE filters, few drops of acid (2 mol/L of Methanesulfonic acid Solution) were used on the filter before adding purified water to avoid the filter to stick on the tubes. Ions were extracted from the samples using an electric shaker, model SR-2W (Figure 2.15d) at the speed of 110 (r/min) for 20 min. After extraction, the filters residues were separated from the solution and transferred in sterile tubes by using sterilized syringes (figure 2.15e). The syringes

were connected to filters designed to remove the particulate matters susceptible to damage the column. The final step of the sample preparation was to fill up the tubes adapted for the ion chromatography instrument with the sampled solutions (Figure 2.15f).

- **DRI Model 2001 Thermal/Optical Carbon Analysis**

The carbon analyzer Model DRI 2001 developed by the Desert Research Institute (DRI) was used to quantify the carbonaceous elements contained in different filter samples. The optical carbon analysis is based on the principle of the differential oxidation temperature of organic carbon (OC) compounds and elemental carbon (EC) (Figure 2.16). It relies on the fact that organic compounds volatilize from the sample deposit in non-oxidizing helium (He) atmosphere, while elemental carbon must be combusted in an oxidizer [5].

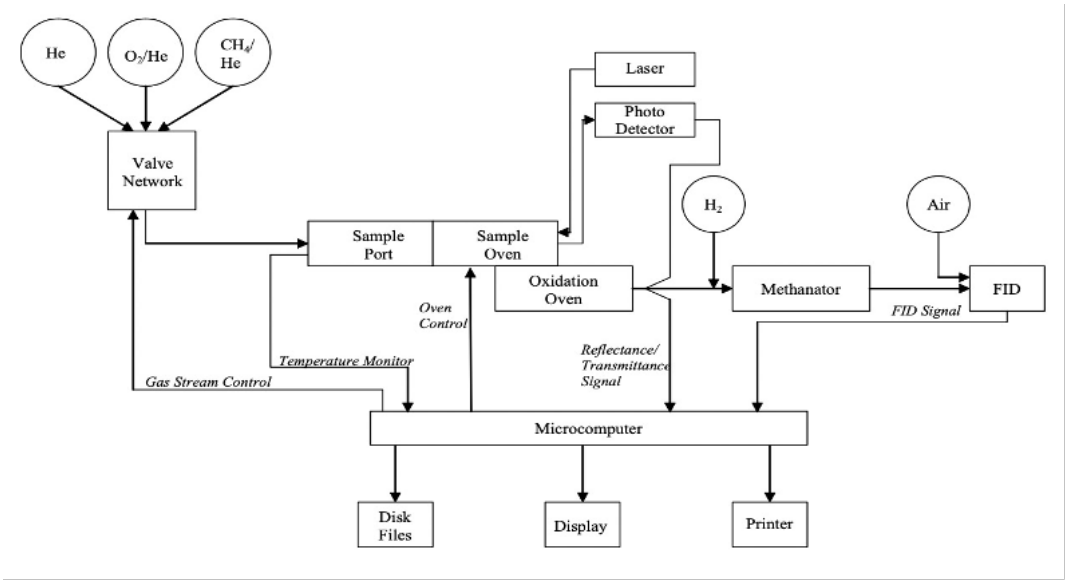


Figure 2.16: Schematic Diagram of DRI Model 2001 Thermal/Optical Carbon Analyzer Adopted from [5]

For the carbonaceous measurement, the quartz filter samples do not require any specific pretreatment but sectioning a 0.505 cm^2 from the filter sample. The 0.505 m^2 punched is loaded into the sample boat (Figure2.17).

Carbon evolves from the filter punch at different temperature to quantify the carbon content. The thermal program will advance to the next temperature or carrier gas mixture once the Flame

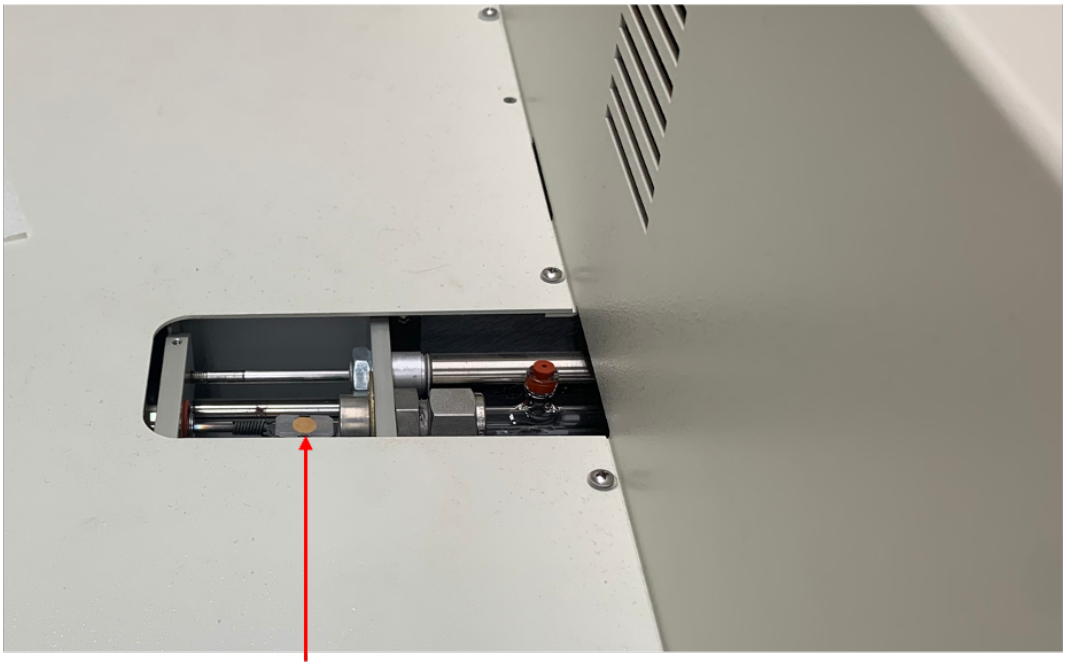


Figure 2.17: Sample loaded in the sample boat

Ionization Detector (FID) signal returns to its baseline. Seven temperature fractions determine the organic and elemental carbon content. In a He-only (99.99%) atmosphere different peaks of organic carbons evolve from 25 to 140, 140 to 280, 280 to 480 and 480 to 580 °C corresponding to four peaks of organic carbons (OC1, OC2, OC3, OC4 respectively). Plus, pyrolyzed organic carbon evolving after O_2 is introduced to the gas flow at 580 °C. Similarly, three peaks of elemental carbon (EC1, EC2, EC3) evolve from the filter punch in a 98% He and 2% O_2 atmosphere at 580, then 740, and from 740 to 840 °C minus any pyrolyzed organic carbon . DRI 2001 is equipped with a laser, therefor, can monitor the reflectance and transmittance, largely dominated by the presence of light absorbing EC. The portion of the EC peak corresponding to pyrolyzed OC can be accurately assigned to the OC fraction. Such correction is necessary to avoid the overestimation of EC by the interference of OC. The lowest detection limit for total organic carbon, total elemental carbon and total carbon are respectively 0.45μg/m^2, 0.06 μg/m^2 and 0.45 μg/m^2 respectively [5].

- **Inductively coupled plasma mass spectrometry (ICP-MS)**

The Inductively Coupled Plasma Mass Spectrometry model XSeries2 ICP-MS (Thermo

Fisher Scientific Inc) was used to determine the elemental trace metallic content. ICP-MS determines low concentrations in the range of ppb (part per billions) and ultra-low-concentration in the range of ppt (part per trillion) of metal components [49]. The injected sample will be first nebulized in a spray chamber then, will be atomized and ionized inside the plasma torch. The produced ions penetrate the mass spectrometer (MS). In the MS, ions will be separated according to their mass by a quadrupole. The ions will be quantified by measuring the electric pulls produced (2.18). The detector will quantify the concentration based on the ion signal. External calibration using multi-element standard was performed at beginning and end of analysis. Sample concentrations were calculated using the slope of the calibration curve.

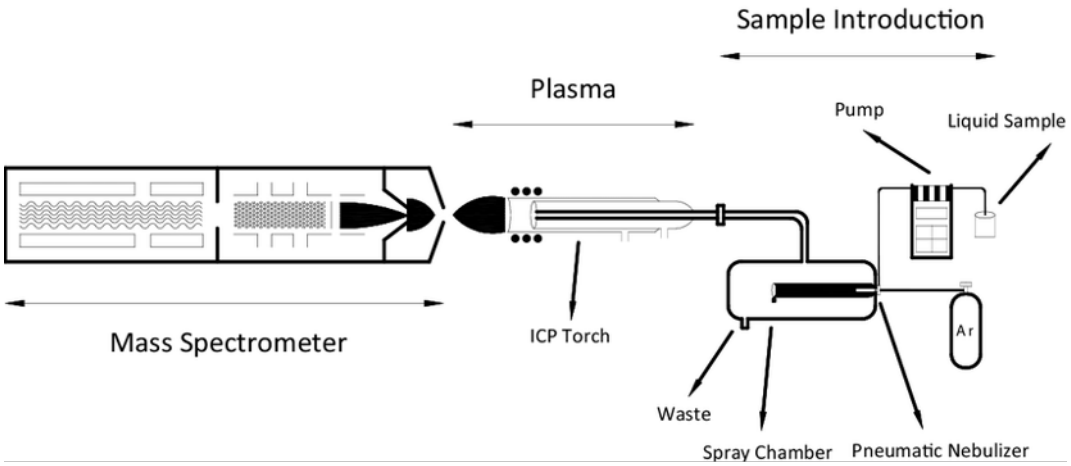


Figure 2.18: Schematic diagram of inductively coupled plasma-mass-spectrometry (ICP-MS)

Sample preparation

Portions of the filter samples (quartz and PTFE) were sectioned using ceramic scissors. First, 3 mL of (50%) hydrofluoric acid (HF), 6 mL (70%) of nitric acid (HNO_3) and 1 mL (30%) of hydrogen peroxide (H_2O_2) were added to the sectioned filters for digestion. The digestion process dissolves the analyst and decompose the solids while avoiding the loss or the contamination of the samples. Then, samples were digested using a microwave (Ethos 900, Milestone General Inc., USA) for 2 min. The power of the microwave was 250 W. The second step was the acids evaporation using a hot plate. The digested samples were heated at 200°C until they were reduced to about 0.1 mL. Last, nitric acid (1 mol/L) was added to the samples till 15 mL for dilution [45] [50]

Calculation methods

The data obtained from the collected filters were used to provide various information on nature of PM and their effects. Bellow the calculation methods.

- **Ion equivalent**

The ion balance was determined from the ratio of cation micro-equivalent to anion micro-equivalent to indicate the balance of ionic species in particles. A value close to 1 suggests a neutral ionic stage; a value over 1 indicates an acidic stage and, a value below 1 indicates alkaline stage. Equations 1, 2 and 3 were used to calculate anion micro-equivalent (AME), cation micro-equivalent (CME) and the ionic balance.

$$AME = SO_4^{2-}/48 + NO_3^-/62 + Cl^-/35.5 + F^-/19 + NO_2^-/46 + Br^-/80 \tag{2.4}$$

$$CME = NH_4^+/18 + Na^+/23 + K^+/39 + Mg^{2+}/12 + Ca^{2+}/20 \tag{2.5}$$

$$\text{Ionic balance } = \frac{AME}{CME} \tag{2.6}$$

Where, *AME* is the anion micro-equivalent (μeq/L) and cation micro-equivalent *CME* (μeq/L).

- **Enrichment factor**

Enrichment factor (EF) is a widely used to approach in environmental studies to estimate the contribution of anthropogenic activities to the concentration of elements naturally present in the environment. The equation bellow was used to determinate EF.

$$EF = \frac{C_x/C_{Al}}{C_x(crust)/C_{Al}(crust)} \tag{2.7}$$

Where; EF is the enrichment factor, C_x is the concentration of a Metal x in the sample,C_{Al} is the concentration of the reference element; Aluminum (Al) in the sample, C_x(crust) is the concentration of the metal x in the earth crust, C_{Al} (crust) is the concentration of Al in the crust.

- **Chemical Mass Balance (CMB)**

Chemical mass balance is a receptor model that can be used to determine the source of environmental pollution from the composition of chemical species. Receptor models use the chemical and physical characteristics of gases and particles measured at source and receptor to both identify the presence of and to quantify source contributions to the receptor concentrations [51]. The model requires a prior knowledge of the sources and their uncertainties (as input predefined source profiles), usually chosen to represent known primary source emissions [52]. These models attempt to derive source profiles from the co-variation in space and/or time of many different samples of atmospheric constituents that originate in different sources. These profiles are then used in a CMB solution to quantify source contributions to each ambient sample. CMB is given by the following equation.

$$C_i = \sum_{j=1}^{J} F_{ij}\, S_j \qquad \text{For i=1 to N} \tag{2.8}$$

Where; *Ci* is the ambient concentration of elements and their uncertainties. *Fij*, the fraction of source profiles and their uncertainties. *Sj* represents the source contribution and their uncertainties. *N* is the number of chemical species and *J* is the number of sources. Here, *Ci* and *Fij* are inputs and *Sj* is the output.

- **Principal Component Analysis (PCA)**

The principal component analysis (PCA) was used in this study to evaluate the source contribution on chemical species in the ambient air samples and to determine the possible ambient air pollution sources. The fundamental principle of PCA is that a strong correlation may exist between components from the same source. Principal component analysis is a dimension reduction method. It reduces the dimensionality of a large data set consisting of a large number of

interrelated variables to a smaller data set without losing much information present in the data set. In PCA analysis, the data are first transformed into a standardized form by normalizing the concentration of each element in each sample with respect to the mean value and standard deviation for the element. This is achieved by transforming to a new set of variables, called the principal components (PCs), which are uncorrelated, and which are ordered so that the first few retain most of the variation present in all of the original variables [53]. Assuming a linear relationship between variables (species concentrations) and a number of p factors (sources), PCA is expressed as:

$$Z_{ij} = \sum_{k=1}^{p} g_{ik}\, h_{kj} \tag{2.9}$$

Where; Z_{ij} is the reduced mass concentration of i^{th} element in j^{th} sample, k = 1,.....,p is the number of factors sources, while g_{ik} and h_{kj} respectively are factor loading of the i^{th} element to the k^{th} component (source) and factor scores of the k^{th} component (source) to the j^{th} sample [32].

- **Health risk assessment**

Health risk assessment is a useful tool to determine the possibility of any harmful effects that might occur from the exposure to heavy metals. The equations for the health assessment have been adopted from the US EPA health risk assessment models [54].

Non-carcinogenic risk

Non-carcinogenic risks assessment determine health risks that do not include cancers. The health risk from metals not identified as carcinogenic is evaluated by determining the Hazard Index (HI) and/ or the Hazard Quotient (HQ).

$$HI = \sum HQ \tag{2.10}$$

$$HQ = \frac{EC}{RfC * 1000} \tag{2.11}$$

Where; *HI* is the hazard index, *HQ* is the hazard Quotient, EC is the exposure concentration (in $\mu g/m^3$) and RfC (mg/m^3) is the inhalation reference concentration.

$$EC = \frac{(CA * ET * EF * ED)}{AT} \tag{2.12}$$

Where;

$$AT = ED * 365\ days * 24/day \tag{2.13}$$

EC is the the exposure concentration, *CA* is the concentration of a metal ($\mu g/m^3$), *ET* is the exposure time (hours/day), *EF* is the exposure frequency; assumed to be 350 days (days/year), *ED* is the exposure duration (years), *AT* is the average time (hours).

Non-carcinogenic impacts may occur when HI and/or HQ is over 1, while harmful health impacts are not expected when the value is lower than 1 [55].

Carcinogenic risk

Carcinogenic risk assessment (CR) determines the risk of developing cancer from the exposure to toxic metals. The total *CR* for health purpose should be ranging from 10^{-6} to 10^{-4} [56]. A CR value higher than 10^{-6} is unsafe and a value more than 10^{-4} is unacceptable.

$$CR = EC * IUR \tag{2.14}$$

Where; *CR* is the carcinogenic risk, *EC* is the exposure concentration and IUR ($\mu g/m^3$) is the Inhalation Unit Risk. *RfC* and *IUR* values for each metal were obtained from the EPA Integrated Risk Information System (IRIS) [57].

According to EPA, at least five metals are expected to be carcinogenic to human. These are As, Cd, Cr (VI), Be and Ni. Pb was identified as probable carcinogenic. Therefore, in this study, the carcinogenic risk assessment of the six aforementioned metals were estimated. And, the non-carcinogenic risk of Cr, Mn, Ni, As, Cd and Be were assessed. Pb was excluded for the non-carcinogenic risk assessment calculation as the RfC was not available.

Chapter 3

Results and discussion

Personal Exposure to Fine Particles ($PM_{2.5}$) in Northwest Africa: Case of the Urban City of Bamako in Mali

Particulate matter (PM) is one of the most widespread pollutants in the atmosphere and has attracted the interest of numerous air-quality researchers. PM exists in the atmosphere as solid or liquid suspensions. They originate from natural sources, volcanic eruptions, sea salt, wildfires, and anthropogenic sources, like road traffic, biomass combustion, and waste incineration. They can be dispersed by wind. When directly emitted from pollution sources, particles are referred to as primary PM. Secondary PM is produced by the reaction of primary precursor gases entering the atmosphere. Particle sizes differ from a few nanometers to hundreds of micrometers. They are classified according to size from smallest to largest as the Nuclei mode (ultrafine fraction), Aitken mode (fine fraction), Accumulation mode, and Coarse mode. The mass distribution is dominated by the Accumulation and Coarse modes [9].

Depending on their size, the various PM types have multiple harmful effects on the environment and human health. Smaller particulate matter can undergo long-range transport and, in addition to local impacts, generate regional and global impacts. They are most involved in atmospheric reactions by natural processes. They directly affect climate change through their role as cloud condensation nuclei [9] and reduce visibility in the troposphere by scattering solar radiation [58]. Worldwide, many studies have provided evidence of the effects of PM on human health, especially the fine and ultrafine fractions, as they can reach the deepest regions

of the respiratory system. Short-term variation and levels of urban particulate air pollution are associated with increases in lung function deterioration, respiratory diseases, number of hospital admissions, and mortality from cardiorespiratory problems and cancers [11]. Countries including China, India, France, Italy, and the United States have reported health issues related to exposure of $PM_{2.5}$ microns or less in diameter [59] [60] [61] [62]. However, information is scant in developing countries.

In Africa, air pollution has reached a significant scale. The average concentration of $PM_{2.5}$, ranging up to 507 $\mu g/m^3$, has been recorded in multiple African cities. The concentrations exceed the World Health Organization Air Quality Guideline (WHO AQG) in nearly all African cities where $PM_{2.5}$ data are available [63] . Rapid population growth has led to the increased use of natural resources and the emission of chemical molecules that affect ecosystems. Air pollution in Africa and the resulting health effects are strongly related to socioeconomic status. The majority of risk factors, such as biomass combustion, transportation (vehicle age, motorcycle, taxis, and buses), unpaved roads, and street food preparation are more pronounced [64] [65]. The majority of households in developing countries burn biomass fuels in open fireplaces, and the car fleets are older, poorly maintained, and use low-quality fuels with high lead concentrations, which generate high levels of pollutants [66]. Household air pollution from solid fuels contributes to ambient particulate matter pollution and has been identified as the second disease burden in most of sub-Saharan Africa, and the fourth globally [67] [68]. To overcome these issues, international institutions have established international development goals in sustainable development (SDGs). The vehicle fleet is predominately old in the city of Bamako, located in Mali in West Africa, as well as in many other developing countries that include Lagos in Nigeria [63] and Addis Ababa in Ethiopia [69]. Legislation on the importation of low-quality fuels that are potential sources of major pollutants including nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) is extremely lax. For instance, the importation of diesel fuel with a sulfur content of 10,000 ppm is legal in Mali, while the threshold allowed in Europe is only 10 ppm [70]. Recorded NO_2 and SO_2 values of 60 $\mu g/m^3$ and 29 $\mu g/m^3$, respectively, in traffic sites in Bamako exceed World Health Organization (WHO) guidelines [63]. In addition, waste in-

cineration is the most widely used waste management technique. This, releases considerable quantities of fine particles and other pollutants into the atmosphere. Wood and charcoal are resources that account for 78% of the national energy balance [71]. They are extensively used in households and are a major source of PM emissions. In addition, the combustion of insecticides and incense, which produce a considerable amount of PM, is widespread. The city of Bamako is surrounded by hills [72], and so is poorly ventilated. Consequently, the city is subject to stagnant pollutants from the diverse aforementioned anthropogenic sources. The number of patients with respiratory diseases has increased in Bamako during the last few years [14].

There are no published data concerning population exposure to $PM_{2.5}$ particulate matter in Bamako. The present study addressed this. Personal exposure to $PM_{2.5}$ has been investigated in four different groups of local inhabitants. Participants wore a newly developed palm-sized particle sensor ($PM_{2.5}$ sensor) that was positioned in a lanyard on the chest. The $PM_{2.5}$ sensor is portable, light, inexpensive, has low energy consumption and good data storage capacity, and is reliable. Nakayama et al. (2018) described the performance and characteristics of sensors [43]. The data obtained from the present study are essential to inform the local population about their exposure to $PM_{2.5}$ through daily activities and help increase awareness regarding adverse health effects. Additionally, the data could help to better understand the relationship between the control of environmental problems and promoting sustainable development. This study could provide the local government with reasonable strategies to reduce air pollutant emissions. Finally, this study provides background information on $PM_{2.5}$ exposure concentration in this region and can guide further studies on air pollution in Mali.

3.1 Personal exposure to particulate matters

3.1.1 Daily Time-Series of $PM_{2.5}$ Concentration

Although the data presented in this study were collected during the COVID-19 pandemic, we presumed that the pandemic did not influence the results. The restrictions for coronavirus case reduction strategies were no longer applicable in Bamako. Citizens had already resumed their

daily activities (such as commute to work school, shopping). Consequently, outdoor emission sources remained unchanged. Furthermore, household activities (house chore, cooking and other combustion sources) were sustained as they were not related to the COVID-19 restrictions in Bamako.

Office workers (OW)

Six participants were OW. Figure 3.1a shows a typical $PM_{2.5}$ concentration variation by OW6 between 7-9 October 2020. The air conditions of OW were mainly categorized as home, commuting, office, and home (IST/ICS). OW6 was exposed to a 3-day average of 50 $\mu g/m^3$ with daily concentrations of up to 102 $\mu g/m^3$. The green color in the figure represents the $PM_{2.5}$ concentration at home with an average value of 10 $\mu g/m^3$ and a maximum value of 29 $\mu g/m^3$. The recorded concentrations during the commute to work of OW6 averaged 21 $\mu g/m^3$ with a maximum of 79 $\mu g/m^3$. The concentration in the office, represented by the blue color, averaged 16 $\mu g/m^3$ with a maximum of 33 $\mu g/m^3$. A higher average concentration of 34 $\mu g/m^3$ was recorded during the participant's break time, represented in brown in the figure. During break time, office workers usually commute for lunch. This explains the observed concentration on the 07^{th} and 08^{th} of October around noon time.

The red color in the figure shows concentrations at home when the participant was using insecticides (IST) and incense (ICS), which are popular in the region. The average and maximum values were 163 $\mu g/m^3$ and 460 $\mu g/m^3$, respectively. The home air with the use of insecticides and incense was separately categorized from the period when these products were not used, due to the large differences in concentration. ICS is widely used in Bamako to provide a pleasant scent in the home and is part of the Malian culture. IST are used to prevent mosquito bites and reduce the risk of malaria. These products were typically used every day by the participants.

All the participants had similar daily patterns involving approximately 2 h of driving and approximately 7 h of office work. With only a few exceptions, participants had similar exposures during the same activity. OWs were exposed to approximately 10 $\mu g/m^3$ at home on a

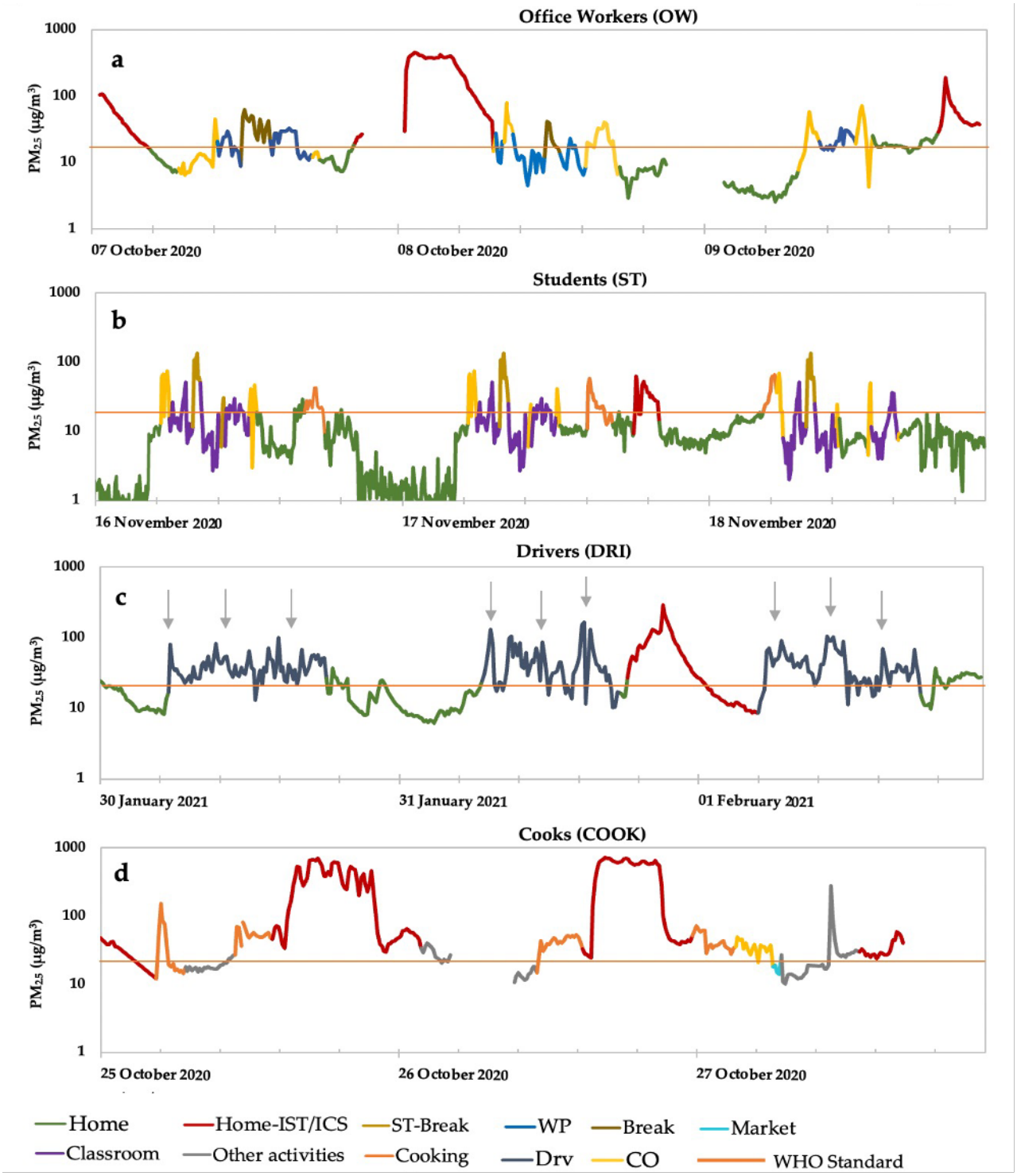


Figure 3.1: Typical daily personal profile adopted from OW6 (a), ST1 (b), DRI3 (c), and COOK1 (d) between September 2020 and February 2021. WHO: World Health Organization, IST/ICS: insecticide/incense, OW: office workers, ST: Students,WP: Workplace DRI: Drivers, CO: Commute, Drv: Driving

daily average, as seen for OW1, OW2, and OW3 (Table 3.1). However, their average exposure increased to 66 μg/m^3 with the use of IST/ICS (OW4). The combustion of the products released very high $PM_{2.5}$. OW4 presented an average concentration of 305 μg/m^3 up to 746 μg/m^3 in 10 minutes periods. OW5 presented a lower average concentration of 160 μg/m^3 (Table 3.1 and Figure 3.1a). The difference in the room conditions (aeration and size) might have resulted in the difference in concentration during the use of specific products.

Table 3.1: Summary of $PM_{2.5}$ concentrations (μg/m^3) during daily activities of office workers. Numbers in parentheses show the exposure time (hours). OW: Office worker; ISC: Incense; IST: insecticide; avg: average

		Home	Driving	Workplace	Home (IST/ICS)	Cooking	Beauty salon	Break	Daily avg
OW1	3-Sep	10	28 (1.0)	5 (6.0)					10
	4-Sep	10	28 (1.3)	5 (4.8)					10
	5-Sep	10	28 (0.8)	4 (5.2)					09
OW2	8-Oct	5	30 (0.3)	33 (10.3)					10
	9-Oct	11	66 (1.0)	46 (4.7)					20
	10-Oct*	9	16 (4.3)						
OW3	14-Sep	5	44 (2.7)	4 (3.5)					09
	16-Sep	6	23 (1.0)	7 (9.5)					7
	17-Sep	7	26 (3.0)	7 (5.7)					9
OW4	24-Sep	7	48 (3.3)	5 (7.0)	305 (4.3)				66
OW5	26-Sep*	18			160 (3.2)	43 (2.0)			
	27-Sep*	9	32 (1.7)				19 (1.7)		
OW6	07-Oct	10	12 (3.3)	20 (5.5)	48 (4)			40 (2.1)	22
	08-Oct	7	23 (3.6)	12 (5.1)	276 (3.1)			24 (1.2)	47
	09-Oct	11	23 (2.3)	22 (3)	61 (6.8)			52 (0.6)	29
Activities	avg	8	28 (2)	14 (7.3)	154 (4.2)	43	19	37.3 (1.3)	

**These days involve data for a part of the day*

The air condition in the workplace also affected the daily exposure. OW2 had a worse condition in the workplace with over 30 μg/m^3, which increased the daily exposure of OW2 to twice that of OW1 and OW3. OW2's office room is located closed to the building's restaurant. Additionally, the yard at the workplace is unpaved. The restaurant activities and the dust resuspension from the dry ground can explain the higher exposure for OW2 during working hours

(Table 3.1). As shown in Figure 3.1a and Table 3.1, the highest exposures for OWs generally occurred during the use of IST/ICS and the commute.

Students (ST)

Figure 3.1b shows the daily representative $PM_{2.5}$ concentration variations for one individual (ST1) from 16–18 November 2020. The microenvironments and activities describing air conditions for ST1 were mainly home, commuting, school (classes), break time at school (outside), and home (ISC/IST). The green color represents the concentration of $PM_{2.5}$ at home (average concentration 8 $\mu g/m^3$). The participant's room was located near the kitchen, which increased the average concentration from 8 to 29 $\mu g/m^3$ during cooking, represented in orange. Yellow indicates the concentration during the commute (walking or driving) between home and school, which averaged 37 $\mu g/m^3$ up to 74 $\mu g/m^3$. Heavy-traffic areas emitting high levels of $PM_{2.5}$ have a higher health impact than other pollutants on pedestrians [73]. Purple indicates the concentration at school during classes, which averaged 14 $\mu g/m^3$ up to 52 $\mu g/m^3$. The highest concentration for ST1 was observed during break time, with an average and maximum value of 80 and 133 $\mu g/m^3$, respectively. The high concentration during break time can be explained by soil dust resuspension, as the schoolyard was dry (Figure A.3). The use of ICS is represented by a red color. The average and maximum concentrations were 34 and 62 $\mu g/m^3$, respectively.

In the ST group, the daily concentration was affected by the level of $PM_{2.5}$, during the commute and break time. Generally, in Bamako city, students commute between home and school by walking, by car or by motorcycle. ST1 was commuting by walking and by car during the sampling period. Higher exposure to $PM_{2.5}$ was observed during the commute by walking; 42 $\mu g/m^3$ on average compared to the commute by car 34 $\mu g/m^3$ on average (Figure 3.1b). During the commute by walk, several factors can contribute to the higher exposure to PM. Including dust resuspension from walking and vehicle as well as emissions from engines. Children by their young age are closer to the ground. Which is another factor that could contribute to the higher exposure. Similarly, in OW group, dust resuspension was identified as a contributing factor to PM exposure. This suggest that local conditions (unpaved ground) can be a factor

contributing to $PM_{2.5}$ exposure in the urban city of Bamako.

Also, ST1 presented higher concentrations on November 16 and 17, with average concentrations of 32 and 31 $\mu g/m^3$, respectively, compared to November 18, with an average concentration of 9 $\mu g/m^3$. ST2 had a higher concentration at home, resulting in an increase in the daily concentration compared to ST1 and ST3 (Table 3.2).

The findings indicate high exposure to $PM_{2.5}$ both indoors and outdoors for the ST group.

Table 3.2: Summary of $PM_{2.5}$ concentrations ($\mu g/m^3$) during daily activities of students. Numbers in parentheses show exposure time (hours). ST: Student; ICS: Incense; IST: Insecticide; avg: average

		Home	Commute	School	School (Beak)	Home** (IST/ICS)	Daily avg
ST1	16-Nov	11	40 (0.3)	19 (0.3)	74 (1.2)		17
	17-Nov	12	37 (0.5)	17 (5.9)	68 (1.5)	35 (1.3)	17
	18-Nov	7	32 (0.2)	15 (2.3)	82 (1.2)		14
ST2	10-Nov	24	42 (1.9)	20 (6.2)	26 (0.5)		25
	11-Nov	32	29 (0.8)	6.0 (3.8)	8 (1.5)		18
	12-Nov	15	27 (0.2)	21 (5)	52 (0.6)		24
ST3	30-Jan*	9	28 (7.3)			22 (2)	
	31-Jan*	13				35 (5.2)	
	01-Feb	14		12 (6.3)		20 (2)	14
Activities	avg	14	30 (1.6)	16 (4.3)	52 (1.1)	29 (2.6)	

**These days involve data for a part of the day*

***STs were exposed only to ICS but not to IST.*

Drivers (DRI)

Two microenvironments and one activity were categorizing air conditions for public transportation drivers: home, driving, and home (IST/ICS). These are represented in green, gray, and red (Figure 3.1c). The daily representative $PM_{2.5}$ concentration variations for a public transportation driver (DRI3) from 30 January 2020 to 1 February 2021, are presented. DRI3 was exposed to 14 $\mu g/m^3$ on average at home, increasing to 43 $\mu g/m^3$ on average during work-

ing hours corresponding to driving. The concentration reached 167 μg/m^3 during rush hours, generally between 7:00 to 9:00 a.m., 11:30 a.m. to 1:00 p.m., and 3:30 to 7:00 p.m. (gray arrows in Figure 3.1c). The highest concentration was 81 μg/m^3 on average with a maximum of 290 μg/m^3 recorded at bedtime after the use of insecticides. DRI3 was highly exposed to $PM_{2.5}$, for a considerable amount of time. A typical daily profile on January 31st indicated an average exposure of 47 μg/m^3 up to 167 μg/m^3 from 8:00 to 19:00 and an average concentration of 139 up μg/m^3 to 290 μg/m^3 from 22:00. These times correspond respectively to the participant working hours and sleep time.

All participants showed similar daily activity trends with more than 10 h of driving per day and 42 μg/m^3 as a daily average (Table 3.3). Furthermore, the IST increases the daily average concentration. DRI1 showed a lower daily average compared to DRI2 (November 16 and 17) and DRI3 with the use of IST/ICS recorded during the sleeping hours. The exposure level in the DRI group was highly related to the daily occupation. Resulting in a high exposure concentration for a longer period of time.

Table 3.3: Summary of $PM_{2.5}$ concentrations (μg/m^3) during daily activities of drivers. Numbers in parentheses show exposure time (hours). DRI: Driver; ICS: Incense; IST: Insecticide; avg: average

		Home	Driving	Home (IST/ICS)	Daily avg
DRI1	11-Oct	9	36 (12)		16
	12-Oct	17	43 (12.5)		22
	13-Oct	4	41 (12.2)		17
DRI2	15-Nov	18	37 (10.8)		18
	16-Nov	27	55 (11.8)		32
	17-Nov	20	37 (12.2)	94 (9.5)	58
DRI3	30-Jan	12	40 (12.5)	25 (3)	26
	31-Jan	12	47 (10.8)	139 (1.7)	47
	01-Feb	12	45 (10.2)	35 (2.2)	27
Activities	avg	12	42 (11.6)	78 (4.1)	

Cooks (COOK)

Activities of COOK were limited to food preparation and other household activities, such as cleaning the house, doing the dishes, and the groceries acquisition, indicating the exposure level in this group. Regular daily $PM_{2.5}$ concentration variations are shown in Figure 3.1d, adopted from COOK1 from 25–27 October 2020. COOK1 was exposed to a 3-day average concentration of 128 $\mu g/m^3$. The highest average concentration was observed at home during sleep (228 $\mu g/m^3$). The concentrations during such events reached very high peaks of up to 717 $\mu g/m^3$. Cooking time, shown in orange, represented the second-highest average concentration of 42 $\mu g/m^3$ with a maximum of 150 $\mu g/m^3$. A high concentration of 27 $\mu g/m^3$ on average was also observed when COOK1 performed other household activities (gray color). The use of specific products, the use charcoal, and wood as cooking fuel and, the cooking stove not adapted for efficient combustion were sources of exposure to a high concentration of particles during the entire sampling period.

As shown in Table 3.4, all participants showed similar average concentrations recorded at home or during cooking.

Table 3.4: Summary of $PM_{2.5}$ concentrations ($\mu g/m^3$) during daily activities of cooks. Numbers in parentheses show exposure time (hours). OA: Other Activities; ICS: Incense; IST: Insecticide; avg: average

		Home	Commute	Cooking	OA	Home (IST/ICS)	Daily avg
COOK1	25-Oct	29		47 (5.3)	27 (6.2)	217 (3)	56
	26-Oct	26		43 (3.7)	22 (4.3)	315 (10)	147
	27-Oct		35 (2.8)	43 (3.5)	31 (3.8)	409 (6.8)	129
COOK2	24-Oct					14 (4.2)	
	25-Oct	21				880 (2.2)	
	26-Oct	21		43 (2.8)	16 (2.8)	153 (5)	48
COOK3	14-Jan			21 (0.8)		15 (6.3)	16
	15-Jan	14		35 (3.7)	17 (6.3)	37 (0.7)	20
	16-Jan	8		28 (1.8)	27 (7.5)	38 (3.8)	23
Activities	avg	18		41 (3.1)	22 (5.2)	300 (4.5)	

**These days involve data for a part of the day.*

The concentration of $PM_{2.5}$, during the use of insecticide, considerably increased the daily

average concentration. For COOK1, the daily average concentration increased more than two times from October 25, with a concentration at home (ICS/IST) of 217 $\mu g/m^3$ to October 26 and 27, with 315 and 409 $\mu g/m^3$, respectively. In addition, COOK3 showed a lower daily average concentration than COOK1 and COOK2, with a higher average daily concentration at home. The higher PM emission from the use of insecticide was, the higher was the daily average exposure. In the COOK group as well (as in the group of DRI), the occupation was a main exposure factor in addition to the combustion of IST/ICS.

3.1.2 Comparison of Different Groups

Table 3.5 summarizes the $PM_{2.5}$ concentrations of the participants' daily activities averaged for each group. Values relative to different microenvironments and activities are presented along with the duration. The difference in the average daily exposure concentrations including and excluding IST/ICS were also presented for each group and for the overall participants.

Overall, common activities presented high $PM_{2.5}$ concentration; 177 $\mu g/m^3$ on average was observed at home with IST/ICS usage, followed by cooking (42 $\mu g/m^3$), driving and commuting (34 $\mu g/m^3$). From table 3.5, different microenvironments and activities presented different $PM_{2.5}$ pollution level during the sampling period. School break time (31 $\mu g/m^3$), beauty salon (19 $\mu g/m^3$), school during classes (16 $\mu g/m^3$), and home without the combustion of IST/ICS usage (13 $\mu g/m^3$).

The concentrations in the same microenvironments and activities were similar, even in different groups (Table 3.5). OW and ST presented a similar average concentration of 28 $\mu g/m^3$ and 30 $\mu g/m^3$ respectively during the commute time. DRI group presented a higher average concentration during driving attributable to the congestion during rush hours (Figure 3.1c). Indeed, while participants from the other groups were performing other activities (such as taking classes, working at the office, house chore) DRI were driving. Consequently, there were subject to exposure during rush hours throughout the day. Which, more likely explains the higher average concentration for the DRI in traffic (driving and commuting). Furthermore, the cooking

activity displayed a very similar value in the group of OW (43 on average $\mu g/m^3$) and the group of COOK (41 $\mu g/m^3$ on average).

Table 3.5: Summary of $PM_{2.5}$ concentrations ($\mu g/m^3$) during the participants' daily activities. Numbers in parentheses show exposure time (hours)

	OW	ST	DRI	COOK	Average
Home	8	14	12	18	13± 4
Driving/Commute	28 (2)	30 (1.6)	42 (11.6)	35 (2.8)	34± 6
Workplace	14 (5.7)				
Cooking	43 (2)			41 (3.1)	42 ± 1
Beauty salon	19 (1.7)				
School (classes)		16 (4.3)			
Break	37.3 (1.3)	52 (1.1)			
Home (IST/ICS)	154 (4.2)	30 (2.6) *	78 (4.1)	300 (4.5)	177±102**
Daily average	11	19	27	23	20±7
Daily average (IST/ICS)	43	20*	38	77	53±20**

**STs were exposed only to ICS and not to IST.*

*** ST was excluded.*

The difference in exposure related to the daily occupation was evident. The DRI group displayed the highest daily averaged concentration (excluding periods involving usage of IST and ICS) of 27 $\mu g/m^3$, followed by COOK (23 $\mu g/m^3$), ST (19 $\mu g/m^3$), and OW (11 $\mu g/m^3$). The higher values for DRI and COOK were attributed to high $PM_{2.5}$ concentrations during daytime activities of driving and cooking, respectively. On the other hand, the low daytime $PM_{2.5}$ concentrations in offices and schools resulted in lower daily values for OW and ST, as shown in Table 3.5. However, when concentrations with IST/ICS at home were involved in the daily average estimation, the daily average concentration increased significantly. The concentration increased from 20 to 53 $\mu g/m^3$ (Table 3.5), which was twice as large as the WHO guideline of 25 $\mu g/m^3$. OW and COOK participants showed average concentrations of 154 and 300 $\mu g/m^3$, respectively during the use of IST/ICS. In both groups, the participants reported the simultane-

ous use of IST and ICS in the diaries. Drivers presented lower values (78 $\mu g/m^3$), which was attributed to the use of only IST in a microenvironment located near the participants' rooms. The group of students had the lowest concentration (30 $\mu g/m^3$) associated with the combustion of ICS only in the house. This indicates that the emission from IST was greater than the emission from ICS and the use of both products resulted in the greatest personal exposure during the study participants daily lives.

IST/ICS average values from this research (177 ± 102 $\mu g/m^3$) are comparable to the average value reported by Kumar (2014) in India of 256.8 $\mu g/m^3$ [74]. In addition, road traffic $PM_{2.5}$ concentration was 34 ± 6 $\mu g/m^3$ on average; a similar value of $PM_{2.5}$ from traffic was reported by Abera (2020) in Adama-Addis Ababa (33 $\mu g/m^3$), a lower value by Belarbi (2020) in Algeria (19.71 $\mu g/m^3$), and a higher value (42,871 $\mu g/m^3$) was reported by Ariunsaikhan (2020) in Mongolia [75] [76] [77]. Cooking represented 42 ± 1 $\mu g/m^3$, and a similar $PM_{2.5}$ value of 46.6 $\mu g/m^3$ from cooking was reported by Vliet al. (2013) in Ghana [67].

3.1.3 Discussion

Total integrated exposure, which is the product of concentration and exposure time, was calculated for each group to characterize the exposure during different common daily activities (Figure 3.2).

The integrated exposure varied in different microenvironments, depending on the activity and its duration. Special events were frequent and represented the highest integrated exposure for OW, COOK, and DRI (927, 1350, and 320 $\mu g/m^3$ h, respectively). The ST group presented a much lower integrated exposure for these events (78 $\mu g/m^3$ h) compared to the other groups. The combustion of IST/ICS is a common practice in households in a wide area (Africa, Asia, and South America). Although indoor air pollution has been widely addressed in the literature, the use of IST/ICS has received comparatively little interest.

High integrated exposures were also observed during traffic (driving and commuting). The

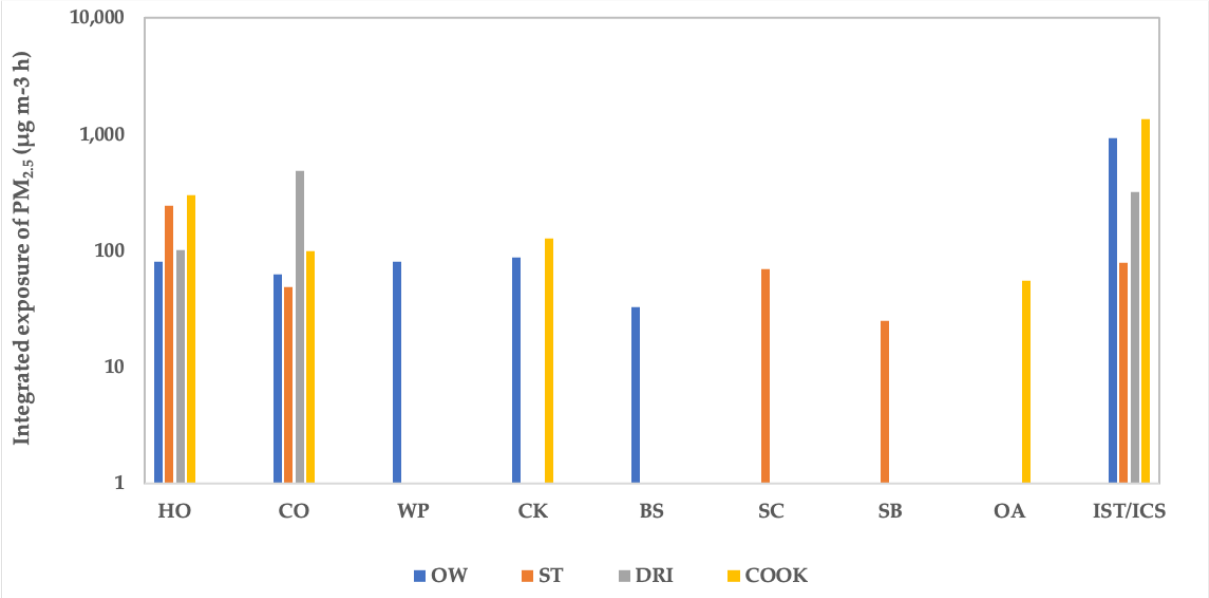


Figure 3.2: Integrated $PM_{2.5}$ exposure for different activities. HO: Home; CO: Commute; WP: workplace; BS: Beauty Salon; SC: School (classes); SB: School (break); OA: Other activities; IST: Insecticide; ICS: Incense; OWs: Office workers;STs: Students; DRI: Drivers

DRI group with a value of 487 $\mu g/m^3$ h presented the highest integrated exposure, followed by OW and ST groups (63 and 48 $\mu g/m^3$ h, respectively). Cooking represented another activity with high integrated exposure values of 127 and 86 $\mu g/m^3$ h in the COOK and OW groups, respectively. In this study, the COOK group presented a significantly high integrated exposure of 432 $\mu g/m^3$ h per day compared to the one presented by Vliet et al. (2013) in rural Ghana of 128.5$\mu g/m^3$ h per day [67]. The cooking fuel (wood or charcoal) and conditions (outdoor cooking) in the rural city of Bamako were similar to the cooking conditions in the rural city of Ghana. Hence, the marked difference might be attributed to the additional daily activities performed by cooks in the urban city of Bamako, such as commuting, cleaning, and grocery acquisition.

Figure 3.3 represents the mean concentration and the mean integrated concentration calculated to characterize the exposure for different activities and microenvironments. The mean integrated exposure, is the product of concentration and exposure time. The integrated exposure for each activity and microenvironment expresses the average integrated exposure observed in the overall participants. Different activities and microenvironments affected the inhabitants' ex-

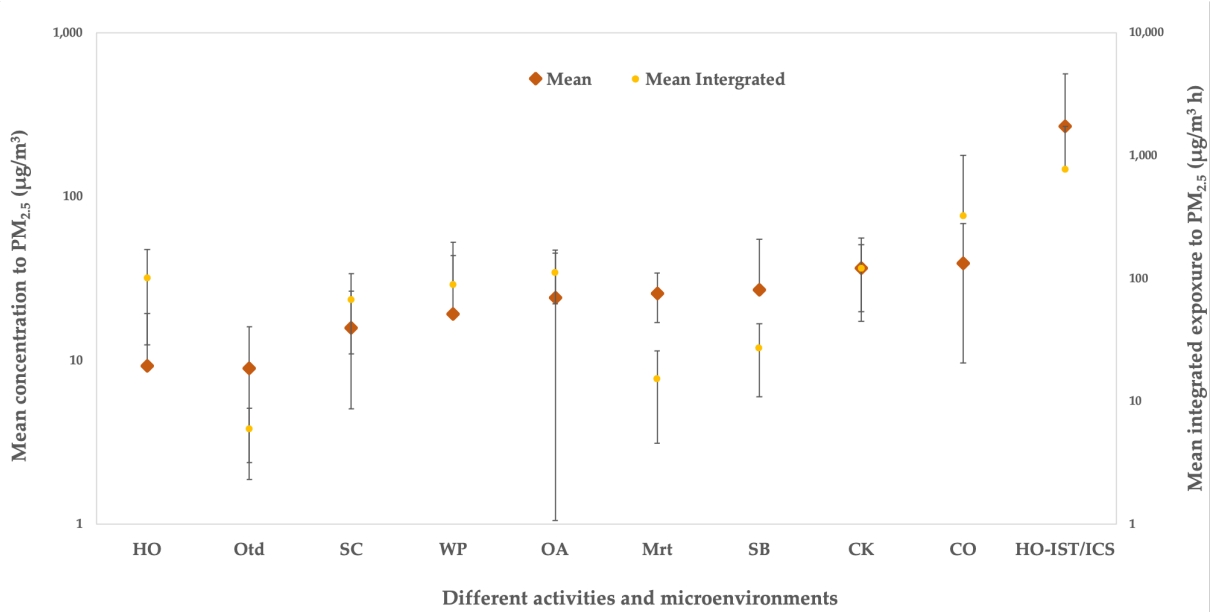


Figure 3.3: Mean concentration, mean integrated exposure and standard deviation of $PM_{2.5}$ for different activities and in microenvironments. Ho: Home Otd: Outdoor; SC: School (Classes); WP: Workplace; OA: Other Activities; Mrt: Market; SB: School (Break); CK: Cooking; CO: Commute; Ist: Insecticide; Ics: Incense

posure level. As shown in Figure 3.3, $PM_{2.5}$ mean concentrations reached high levels for most activities and microenvironments. Lower levels observed for few activities and microenvironments such as relaxing at home indoors and outdoors (neighborhoods) without anthropogenic activities.

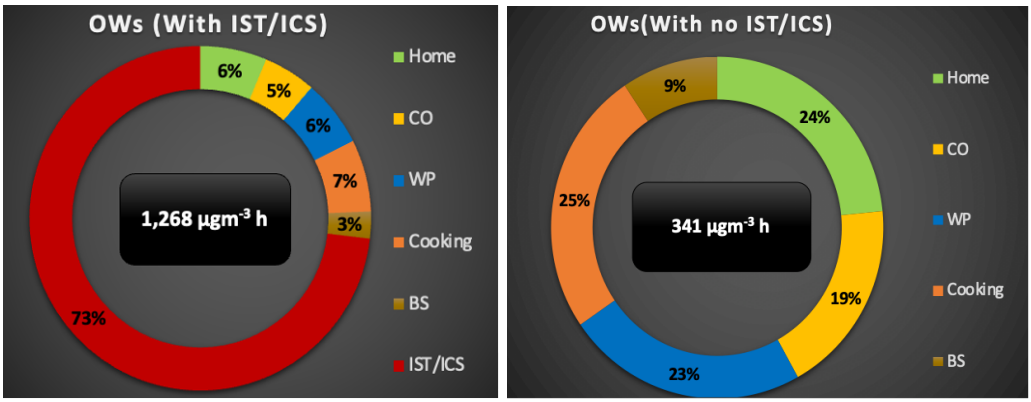
The mean exposure concentration was higher than the mean integrated exposure concentration for some activities and microenvironments. An example of that was observed at the market (Mrt) microenvironment with a mean exposure concentration of 25 $\mu g/m^3$ and an integrated exposure concentration of 15 $\mu g/m^3$ h. Other activities and microenvironments presented lower mean concentration compared to mean integrated exposure. Such as home with 10 $\mu g/m^3$ and 100 $\mu g/m^3$ h respectively for the mean concentration and mean integrated concentration. In the section comparing the exposure concentration in different groups, similar concentrations were observed for the same activities and microenvironments in the different groups. As aforementioned, the integrated exposure value is proportional to the time (from its definition). This implies that the observed higher mean concentration compared to the mean integrated concen-

tration in the participants for a specific activity and microenvironment resulted in the time spent performing the activity or the time spent in the microenvironment.

Both ; mean exposure concentration and mean integrated exposure concentration became significantly higher in the same microenvironment during the used of IST/ICS; from 9 to 267 $\mu g/m^3$ and from 100 to 768 $\mu g/m^3$ h. High values of 39 and 37 $\mu g/m^3$ and, 321 and 120 $\mu g/m^3$ h were also recorded for mean concentration and mean integrated exposure during driving and cooking receptively. Lower but not negligible concentrations were observed for other activities and microenvironments.

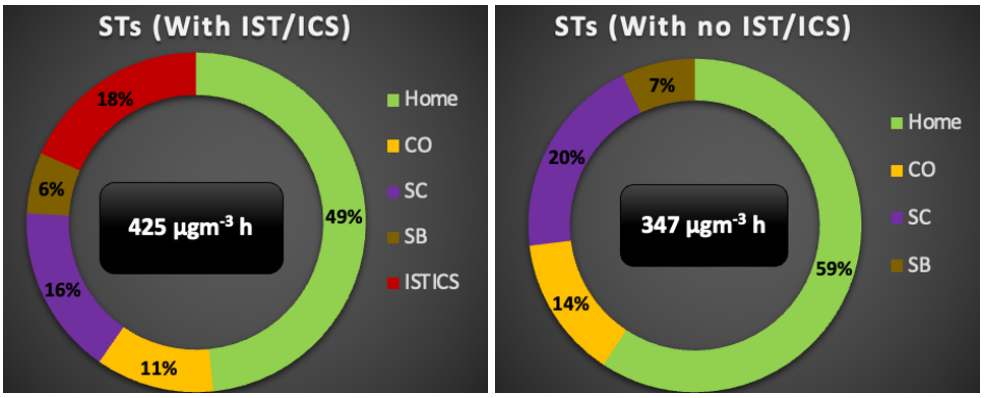
Furthermore, the percentages of integrated exposure attributed to different microenvironments were estimated. The value of the integrated exposure for each microenvironment was divided by the sum of the integrated exposure of all the microenvironments in each group. Figure 3.4 to Figure 3.7 presents the percentages of the integrated exposure for the OW, ST, DRI and COOK group with and without the use of specific products (a and b, respectively). For the OW group, the highest percentage of integrated exposure was attributed to the use of IST/ICS (73%; Figure 3.4a). Without special events, the highest percentage was attributed to cooking (Figure 3.4b). The data in Figure 3.4 indicate the the total integrated exposure decreased by approximately a factor of 4, from 1,268 $\mu g/m^3$ h to 341 $\mu g/m^3$ h, without the combustion of IST/ICS.

For students, there was no significant change in the percentages from the use to the non-use of special products (Figure 3.5). Home remained the microenvironment with the highest integrated exposure followed by the school microenvironment.
For drivers, the highest percentage was observed during working hours corresponding to driving. This including and excluding the use of IST/ICS; 54% and 83% respectively (Figure 3.6). This once more highlight the elevated integrated exposure in the DRI group for the driving activity. Due to their occupation, drivers spend a much longer time in the traffic microenvironment. Consequently, the exposure was strongly related to the occupation. Nevertheless, the total in-



(a) Witth IST/ICS **(b)** With no IST/ICS

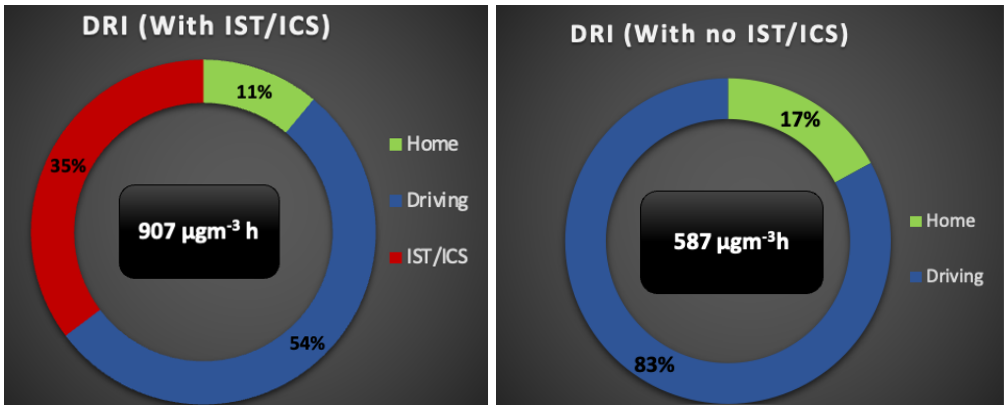
Figure 3.4: Percentage of integrated exposure for different activities and microenvironments for office workers including (a) and excluding (b) the combustion of IST/ICS. OW: Office worker IST: Insecticide, ICS: Incense, BS: Beauty salon, CO: Commute, WP: Workplace



(a) With IST/ICS **(b)** With no IST/ICS

Figure 3.5: Percentage of integrated exposure for different activities and microenvironments for students, including (a) and excluding (b) the combustion of IST/ICS. ST: student, CO: Commute, IST: Insecticide, ICS: Incense, SC: School (classes), SB: School (break)

tegrated exposure considerably decreased with no IST/ICS. From 907 μg/m^3 h to 587 μg/m^3 h. IST/ISC showed a lower percentage due to the combustion in another microenvironment than the one the participants stayed in. The total exposure decreased by a factor of approximately 2 and 1 for the DRI and ST groups, respectively, because of the use of only IST in a closed microenvironment for the group of drivers, and only ICS for students. For the same reason, in these groups, the total exposure decreased by a factor of (approximately) 2 and 1 instead of 4 in the other groups.

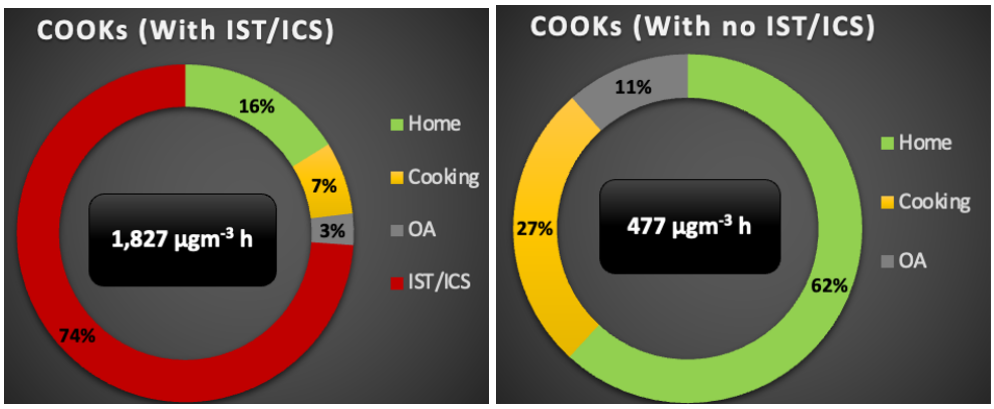


(a) With IST/ICS **(b)** With no IST/ICS

Figure 3.6: Percentage of integrated exposure for different activities and microenvironments for drivers, including (a) and excluding (b) the combustion of IST/ICS. DRI: Driver, IST: Insecticide, ICS: Incense

Similarly, to the OW group, the COOK group highest percentage of integrated exposure was attributed to the IST/ICS use (74%; Figure 3.7a). But with no IST/ICS the highest percentage was attributed to the home microenvironment (62%; Figure3.7b). This is in agreement with Figure 3.3 indicating higher integrated exposure concentration for activities and microenvironment where, participants spent the most time. A decrease from 1,827 μg/m^3 h to 477 μg/m^3 h was observed for cooks with no IST/ICS resulting in a reduction of the integrated exposure of approximately a factor of 4 (as for OW).

This section clearly showed that the use of IST/ICS had a very large contribution to the exposure. Even though houses in Bamako have natural ventilation systems, the windows and doors are usually kept closed while using products, such as IST and ICS. This results to the elevated integrated exposure during IST/ICS combustion in households. Furthermore, this section indicated that there is a relationship Between occupation the exposure to PM. In the DRI and COOK, participant were highly exposed during driving and cooking respectively (Figure3.6 and Figure 3.7).



(a) With IST/ICS **(b)** With no IST/ICS

Figure 3.7: Percentage of integrated exposure for different activities and microenvironments for cooks including (a) and excluding (b) the combustion of IST/ICS. IST: Insecticide, ICS: Incense, OA: Other activities

- **$PM_{2.5}$ Average concentration including and excluding IST/ICS for different groups**

Figure 3.8 represents the average of the maximum, minimum and median concentration of $PM_{2.5}$ to which Bamako's inhabitants can be exposed according to the main occupation. The maximum gives information about the inhabitants' highest average exposure concentration. The minimum represents the lowest average exposure concentration and the median represents the exposure concentration during 50% of the participants 'time over the sampling period.

As shown in the figure, $PM_{2.5}$ concentrations reached very high levels in all the four groups. The concentrations became much higher with used of IST/ICS. An increasing variation of the maximum concentration was observed respectively from the group of OWs with values varying from 98 $\mu g/m^3$ to 723 $\mu g/m^3$, COOKs from 79 $\mu g/m^3$ to 661$\mu g/m^3$, DRIs 109 $\mu g/m^3$ to 207 $\mu g/m^3$, and STs 53 $\mu g/m^3$ to 56 $\mu g/m^3$. The lowest maximum concentration of 53 $\mu g/m^3$ with no ICS exceeds the WHO and AQI standards of 25 and 35.5 $\mu g/m^3$. The minimum concentrations were $\leq$ 7 $\mu g/m^3$ depending on the activity and microenvironment. The median concentration varied from 8 $\mu g/m^3$ to 18 $\mu g/m^3$, 15 $\mu g/m^3$ to 14 $\mu g/m^3$ and 25 $\mu g/m^3$ to 30 $\mu g/m^3$ respectively in the group of OWs, STs and COOKs. The median did not change in the group of drivers and represented 32 $\mu g/m^3$ with and without IST/ICS. Such values corresponded to the participants' exposure level during half of their time. From these results, we can conclude that driving and

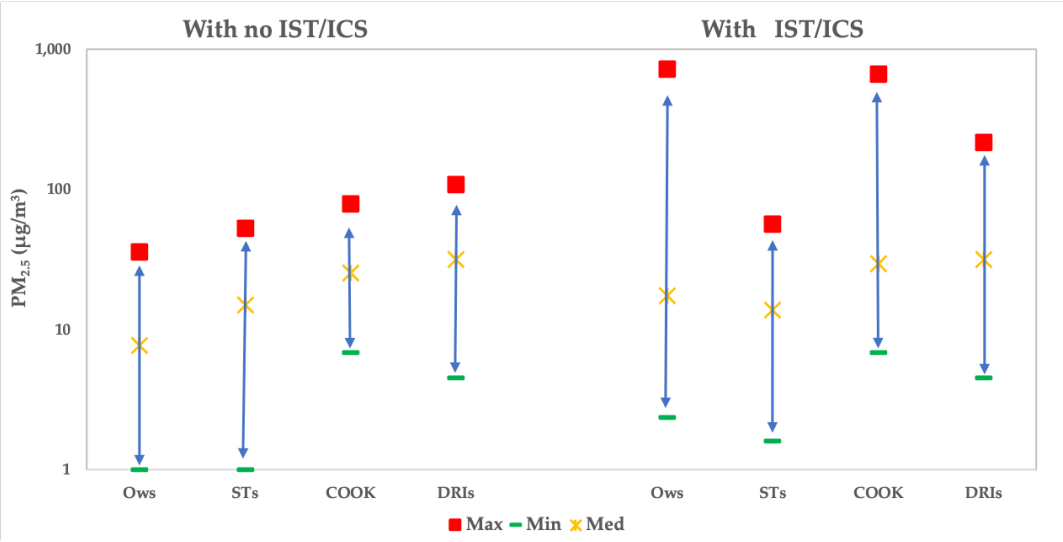


Figure 3.8: Average maximum (Max), minimum (Min), and median (Med) $PM_{2.5}$ exposure concentration in different groups with IST/ICS and with no IST/ICS. IST: Insecticide; ICS: Incens; OW (Office Workers), ST (Students), a (Office Workers), b (Students), c (Cooks), d (Drivers)

cooking are the most exposing daily occupation as they presented the highest values with no IST/ICS. This section gave an estimation of the range of exposure based on the occupation.

- **$PM_{2.5}$ indoor and outdoor exposure**

Figure 3.9 presents the average of the maximum, minimum and median concentration of $PM_{2.5}$ during different typical daily activities indoor (a,b) and outdoor (c).

From Figure 3.9 and Table 3.6 the $PM_{2.5}$ maximum average concentrations reached very high levels for all indoor and outdoor activities and microenvironments. The highest average maximum and median values were attributed to indoor exposure (IST/ICS) and outdoor exposure (driving and cooking). The highest level of 999 $\mu g/m^3$ was observed indoors during the combustion of IST, which is consistent with results presented by Manigrasso et al. where indoor PM emissions were the highest while combustion sources, such as mosquito coil and incense coil, were present [78]. The second highest was attributed to driving (216 $\mu g/m^3$), followed by cooking at a concentration of 150 $\mu g/m^3$. The use of only ICS at home represented another high-exposure microenvironment, with an average maximum exposure of 145 $\mu g/m^3$. The highest median exposure occurred during special events at 82 and 46 $\mu g/m^3$, respectively,

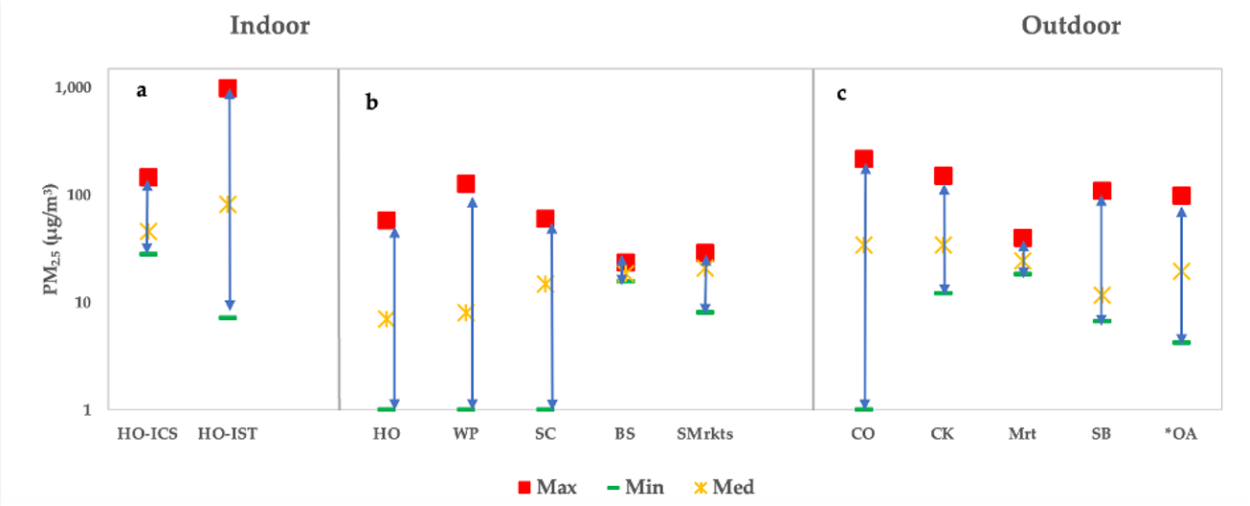


Figure 3.9: Average maximum (Max), minimum (Min), and median (Med) concentrations for different activities and microenvironments indoors (a,b) and outdoors (c). HO: Home, IST: Insecticide, ICS: Incense, WP: Workplace, SC: School (classes), BS: Beauty salon, Smrkts: Supermarkets, Mrt: Open markets, SB: School break, OA: Other activities. * Activities recorded indoors and outdoors.

for IST and ICS. Driving and cooking were 34 μg/m^3. Fifty percent of the exposure concentration was higher than the median values. For most activities and microenvironments, the median concentration exceeded the WHO daily standard of 25 μg/m^3 [79]. The average minimum concentrations were $\leq$ 14 μg/m^3, depending on the activity and microenvironment.

The indoor $PM_{2.5}$ concentration did not exceed 11 μg/m^3 without the combustion of the specific products. Therefore, indoor exposure could significantly decrease with a decrease in the use of IST/ICS. The outdoor average concentration was as low as 9 μg/m^3 in the neighborhood, while the concentration in the yards of houses reached 22 μg/m^3 (Table 3.6). For both indoor and outdoor environments, background concentrations were lower than the observed concentrations during anthropogenic activities. This implies that in Bamako, anthropogenic activities are the most likely factor of exposure, rather than outdoor elevated sources.

Table 3.6: Average concentration of $PM_{2.5}$ for different daily indoor and outdoor activities

Activities/ $PM_{2.5}$ concentration, $\mu g/m^3$					
Indoor	Bedtime (insecticide)	267	Outdoor	Cooking	41
	Home (no insecticide)	7		2 h after cooking	30
	Home (incense)	75		Market	25
	Home (no incense)	11		Yard	22
	School	18		Driving	39
	office	19		Walking neighborhood	9
Others					24

Gender segregation exposure

In Bamako, occupational gender segregation influences the degree of the integrated exposure. All public transportation drivers are men, and cooks are women. According to the WHO, emissions from road traffic have been linked to a wide range of health effects, including effects on the cardiovascular and respiratory systems [79]. Public transportation drivers spend more than 10 h per day working (Figure 3.1c). Thus, they are subject to chronic exposure. Moreover, domestic biomass usage for cooking is one of the major $PM_{2.5}$ exposure sources in developing countries [80]. Associated with domestic and forest fires, cooking has generated global concern for its effects on human health and the environment [81].

In 2010, the use of solid fuels for household cooking resulted in 370,000 deaths and 9.9 million disability-adjusted life years on a global scale [82]. In Mali, wood and charcoal represent more than 75 percent of the household energy needs [71]. Solid fuel is usually combusted in inefficient cooking stoves, producing a variety of health-damaging particles [82]. The effects of air pollution can be observed during pregnancy [83]. Chronic exposure to $PM_{2.5}$ concentrations exceeding 30 $\mu g/m^3$ has been associated with maternal death [64]. Globally, emissions from households' solid fuel burning represented the second largest health risk factor in women, and the third in children on a global scale [84] [67]. In Bamako, children spend a considerable amount of time with their mothers during the first few years of their lives. Nevertheless, women are the most exposed to PM from cooking, suggesting that children are subject to PM exposure from cooking. In addition, unlike males, female OWs perform other activities, especially during

weekends, exposing them to supplementary sources of $PM_{2.5}$. Figure 3.10 shows the gender-related integrated exposure for a female OW. In addition to working, female office workers often cook and take care of the house; therefore, they can be exposed to supplementary $PM_{2.5}$ sources.

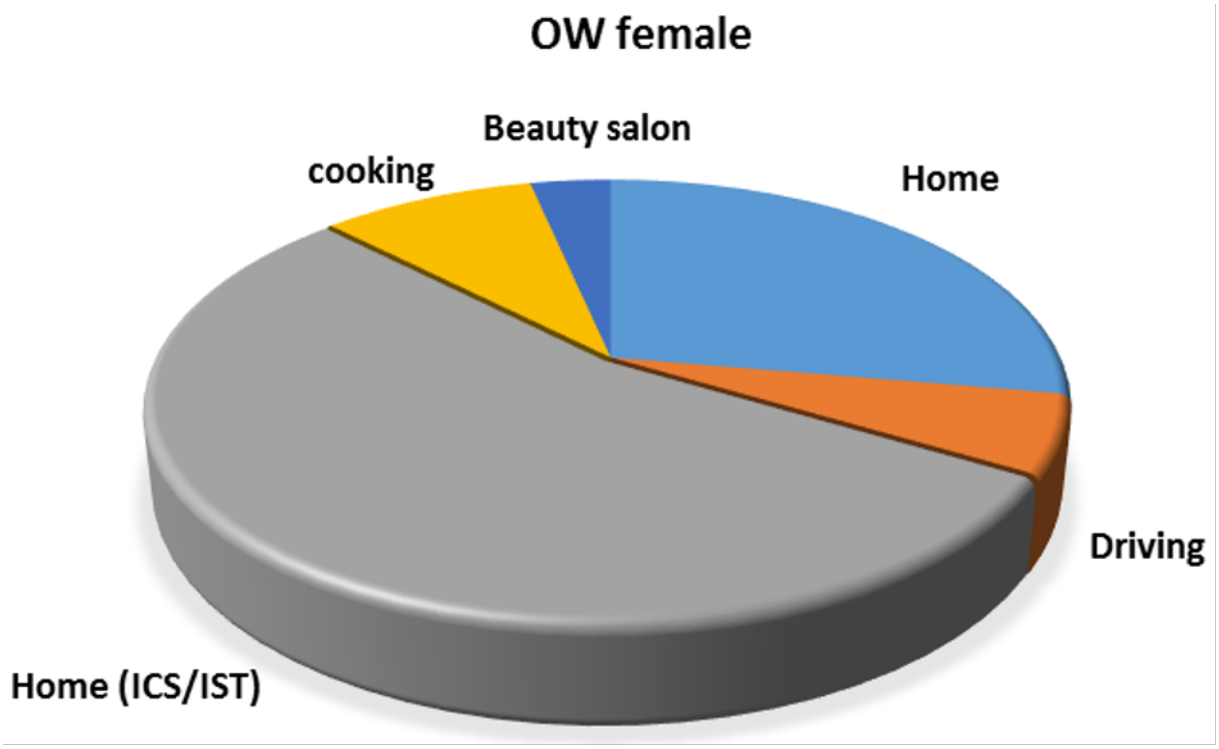


Figure 3.10: Gender-related integrated exposure to $PM_{2.5}$ adopted from OW5 on 26 and 27 September 2020. OW: Office worker; IST: Insecticide; ICS: Incense

The findings allowed us to identify three main common daily activities exposing the population to high concentrations of $PM_{2.5}$. Namely; the combustion of specific products (IST and ICS) in households, the traffic sector , and the use of charcoal and wood as cooking fuel.

Comparison of $PM_{2.5}$ Concentration with WHO Standards and Health Effects

The 24 h average concentrations with and without the use of the specific products were compared to the WHO standards. With no IST/ICS, DRIs and COOKs presented very close values to the WHO's guideline for 24 h exposure concentration of 25 $\mu g/m^3$ [85]. However, OWs and STs displayed lower values than the guideline (Table 3.5). Concentrations were markedly increased in the OW, DRI, and COOK groups with the use of specific products. Concentrations were 1.7, 1.5, and 3 times higher, respectively, than the recommended daily limit. Diverse

health issues from the exposure to high $PM_{2.5}$ concentrations have been mentioned in many studies. For example, Li et al. (2013) [86] reported concentrations exceeding 20 $\mu g/m^3$ as the most harmful to human respiratory health. In the present study, all four groups exceeded the yearly limits of 10 $\mu g/m^3$ with no use of IST/ICS. After considering the use of specific products, the ST, DRI, OW, and COOK groups presented values that were 2, 4, 5, and 7.7 times higher, respectively, than the yearly recommended limit of exposure to $PM_{2.5}$. Burning one mosquito coil can release the same amount of $PM_{2.5}$ as burning 75–137 cigarettes [87]. The combustion of IST has been associated with toxicological effects, morphological alterations, and enzyme perturbations [87]. Asthma, lifetime eczema, wheezing, and rhinitis have been associated with the combustion of IST. ICS burning has been found to be associated with wheezing and rhinitis [88]. Furthermore, from previous studies, the combustion of IST/ICS was found to liberate compounds that are carcinogenic to humans [78].

In Bamako, the incidence of acute respiratory disease increased from 282,000 cases in 2001 to more than 1,500,000 in 2016 [14]. An annual concentration of 10 $\mu g/m^3$ is recommended as the long-term exposure limit. However, a recent study pointed out the effects of long exposure to $PM_{2.5}$ concentrations below the recommended limits [89]. Disease from air pollution results in a decrease in life expectancy, similar to those of other high-priority risk factors and diseases [90].

3.1.4 Conclusion

Relationships between personal exposure to $PM_{2.5}$ and daily activities were investigated in the city of Bamako using palm-sized optical $PM_{2.5}$ sensors. Sampling was performed indoors and outdoors to determine the exposure level for different activities and microenvironments. The participants were divided into four groups according to their main occupation. Three daily activities that highly expose the population to $PM_{2.5}$ have been identified as the most exposed inhabitants.

The study revealed that Bamako's inhabitants are highly exposed indoors while combusting

IST and ICS, where concentrations reached 999 $\mu g/m^3$ on average in a 10 min period. Likewise, participants were least exposed indoors when IST/ICS were not used. Traffic and cooking were identified as high-exposure activities. The concentrations fluctuated among the groups according to their main occupation. Public transportation drivers and cooks were most exposed to $PM_{2.5}$ during their daily activities. Comparisons of our results with the WHO standards indicated that all participants exceeded the yearly exposure limits. Office workers and students presented values within the daily exposure limit without the use of specific products. On the other hand, the group of cooks and drivers exceeded this limit. Although the concentration in students was within the daily limit, the young age makes them more susceptible to air pollution.

Observing the populations actions and avoiding activities that increase pollution could help reduce pollution levels, and consequently, reduce exposure levels. An increase in the level of $PM_{2.5}$ leads to negative effects on health, especially for sensitive people [91]. According to Manigrasso et al. (2017), the impact of particulate matter is higher for sensitive people compared to healthy individuals [92]. Indoor air quality is highly critical for health, since people typically spend most of their time indoors. The use of specific products indoors greatly increased the concentration of $PM_{2.5}$. Therefore, reducing the use of these products could reduce the exposure at specific locations and reduce the risk level of individual total inhaled doses [93]. Moreover, Vliet et al. (2013) suggested that a change in individual behavior could help reduce exposure to $PM_{2.5}$ [67]. Communities, once aware of the potential health effects from their daily indoor actions, can manage their own exposure by avoiding or reducing activities that emit pollution.

This is the first study assessing personal exposure to PM in the city of Bamako. The results provide valuable information about the level of exposure. The results indicated that the main exposure sources were related to lifestyle, IST/ICS use, driving, and cooking. The exposure levels were acute and, the emission sources were strongly related to daily anthropogenic activities rather than natural emissions. This indicates the advantage of personal exposure monitoring.

This research could help increase populations' awareness and should be useful for decision-makers. Consequently, it could help achieve SDG goals, especially regarding health and the environment. For instance, reducing personal exposure to $PM_{2.5}$ through individual daily actions could reduce health impacts and thus contribute to the SDG3 on health and well-being. Furthermore, improving the quality of fuel used by strengthening laws on the fuel quality, using catalytic converters to the vehicle exhausts, reinforcing laws on the annual vehicles' technical inspections, promoting teleworking, and the shift in working hours for different institutions and companies could significantly reduce road traffic-induced pollution. Indeed, teleworking can moderate traffic congestion, thus improving air quality and facilitating urban planning and development [48]. Gradually switching from the use of charcoal and wood to the use of cleaner energies, such as solar energy and bio-gas, could alleviate the exposure to $PM_{2.5}$ from biofuel combustion, as well as pollution from waste incineration. In particular, countries like Mali have high solar potential energy and face waste management issues. These alternatives are economically challenging for developing countries and require time, as proper planning and funds are needed. Therefore, promoting the use of improved cook-stoves with higher combustion efficiency could be practical as a transitional state. Adopting such strategies could help mitigate urban air pollution in Bamako and help achieve SDG7 on affordable and clean energy and SDG13 on climate change at different scales. There is a strong connection between global and local environmental concerns. Although many urban issues are confined within the local scale, many others have regional, or even global consequences. Reducing local emissions has positive repercussions on the mitigation response to regional and global environmental issues, as emissions typically originate from local sources [94].

Our findings demonstrate the need to design appropriate control strategies and continuous monitoring of $PM_{2.5}$, to reduce emissions and protect public health. More work is needed to obtain information on the chemical composition of $PM_{2.5}$, and hence, more information on emission sources and specific health effects in this region.

Chemical characterization of particulate matter from households' activities in Western Sub-Saharan Africa

Nowadays, many researchers have paid a particular attention to air pollution because countless diseases have been linked to air pollutants all over the world. Especially, indoor air pollution which is of a crucial importance for health. Human tend to spend 90% or more of their time in indoor microenvironments [95]. Common daily indoor activities such as cooking, heating, household cleaning results in a substantial air pollutants emission. Several studies have highlighted the effect of air pollution on health. In particular, those of the particulate matters (PM). The chronic exposure to PM in household microenvironments increases the risk for diseases including chronic obstructive pulmonary diseases, heart diseases, stroke, lung cancers disease, cataracts and childhood pneumonia [96] [97].

Households PM pollution is a leading risk factor for mortality and morbidity particularly in developing countries. In 2021, 2.31 million deaths were attributed to indoor air pollution [98]. The situation is particularly alarming in the African region where; more than 800 million people are exposed to indoor air pollution from just food preparation. In low- and middle-income countries people mostly rely on biomass (wood and charcoal) for cooking and heating [99]. Indoor air pollution from the use of such energies in inefficient stoves is one of the major health risk factors. Another indoor source of air pollution is the combustion of incense (ICS). Althougth the use of this product is a very ancient practice; it is still very common in regions

such as Africa and Asia. Inhabitants over these regions use incense for a variety of reasons, including; religious practices, culture and tradition (perfuming clothing, providing a pleasant scent around houses) and meditation. Furthermore, in numerous developing cities, malaria is a disease that presents a serious issue. This infectious disease is communicable by a bite of the female anopheles mosquito. Hence, preventing mosquitos' bite is the main way to reduce malaria transmission. People in these regions highly rely on the use of insecticides (mosquito coils) to repeal mosquitos. However, the combustion of insecticides (IST) and ICS in households largely contribute to indoor PM emission and accumulation especially under inadequate room aeration conditions. These products were also associated to diverse health effects [100] [78] [87]. ICS smoke can affect different part of the body (eyes, nose, throat and skin). Burning ICS have been linked to respiratory problems, asthma, allergies, wheeze and was identified as a factor increasing lung cancer, cardiovascular mortality and stroke mortality [101]. Similarly, the use of IST (mosquito coils) has been associated with numerous health issues varying in severity from irritations, allergies to chronic respiratory problems and cancers [102] [92].

In Bamako, Mali all the aforementioned household emission sources are common. The main household energy sources for cooking are wood and charcoal. These represent 90% of the national energy needs [103]. ICS use is an integral part of the culture. Mainly used by women in households, this practice is considered a significant part of womanhood in addition to the reasons mentioned earlier. Plus, the use of IST is very popular to prevent mosquitos bite likewise, malaria which is one of the leading causes of mortality. As a matter of fact, 1698 death were attributed to malaria in 2020 [104] [105]. Therefore, the population in this urban city is clearly one of the most prominent to PM exposure in households microenvironments.

Our previous study, provided evidence that the level of $PM_{2.5}$ was above the WHO standards in Bamako city. The exposure levels were 3 and 7.5 times higher than daily and yearly limits, respectively. Cooking and the use of IST and ICS were identified as the most exposing households' activities. The recorded values for these activities were 42 ± 1 $\mu g/m^3$ for cooking and 177 ± 102 $\mu g/m^3$ for IST/ICS on a daily average [100]. The exposure to PM regardless

the toxicity triggers human health. The toxic elements can enhance the harmful effects. Heavy metals largely detected in PM are persistent hence, can enter the food chain and bioaccumulated in organisms. They can cause damage to important organs such as brain, lung, kidney, liver and, deteriorate muscular and physical functions [10] [106]. In addition to knowing the exposure level to PM, investigating the chemical composition is necessary to evaluate the health risks. Therefore, we initiated this study to advance our understanding on the chemical composition and relative toxicity of PM originating from households' activities. The main objectives of this research were to determine the chemical composition of PM emitted from the activities producing the greatest exposure and to evaluate the possible health risks.

In this study, we collected PM on quartz and polytetrafluoroethylene (PTFE) filters at the specific household emission sources using filter packs and, analyzed the ions, the carbons (organic carbon and elemental carbon) and the metal composition. Our results gave insights into the households' PM composition in the urban city of Bamako. This study is the first that provided information on the chemical composition of PM from different household emission sources and the associated health risks. As providing evidences based on researches is a key to initiate pollution mitigation strategies. We believe that our findings could be useful in promulgating effective plans for the air pollution control and the public health improvement in this region.

3.2 PM chemical composition characterization in households

$PM_{2.5}$ concentration significantly varied from a sampling source to another. The average concentration for cooking using charcoal and wood were 28.9 ± 21.9 $\mu g/m^3$ and 47.4 ± 19.1 $\mu g/m^3$ respectively. The average concentration for ICS and IST burning was 331.9 ± 296.2 $\mu g/m^3$ and 310.6 ± 172.8 $\mu g/m^3$ respectively. These values are very high compared to the $PM_{2.5}$ exposure standards [107] [13]. The TSP collected on filter provided information on the chemical composition of the PM collected at different households emission sources.

3.2.1 Different chemical components

Ion composition

In this study the concentration of seven anions (SO_4^{2-}, NO_3^-, Cl^-, F^-, PO_4^-, NO_2^-, Br^-) and five cations (NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}) were determined for different emission sources. PO_4^- concentration was under the detection limit for all the samples therefore, it was excluded from the data analysis. Figure 3.11 shows the average ionic mole fraction. Different distribution was observed for each emission source.

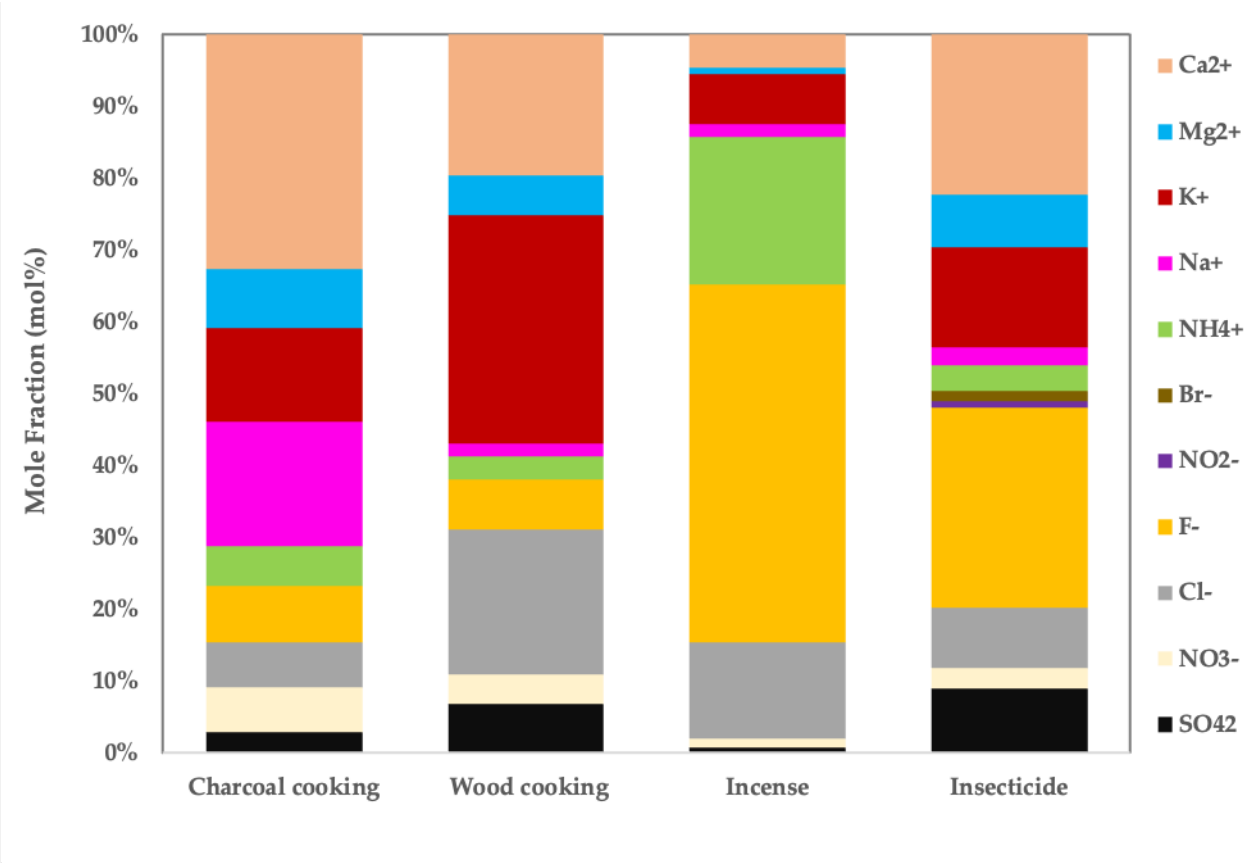


Figure 3.11: Ion contribution in different samples. IST: Insecticide, ICS: Incense

The samplings at cooking sites were performed for two different types of cooking fuel (charcoal and wood). The ion content for cooking using charcoal was dominated by Ca^{2+} (33 mol%), Na^+ (17 mol%), K^+ (13 mol%). And, the order was $Ca^{2+} > Na^+ > K^+ > Mg^{2+} > F^- > NO_3^- > Cl^- > NH_4^+ > SO_4^{2-}$.

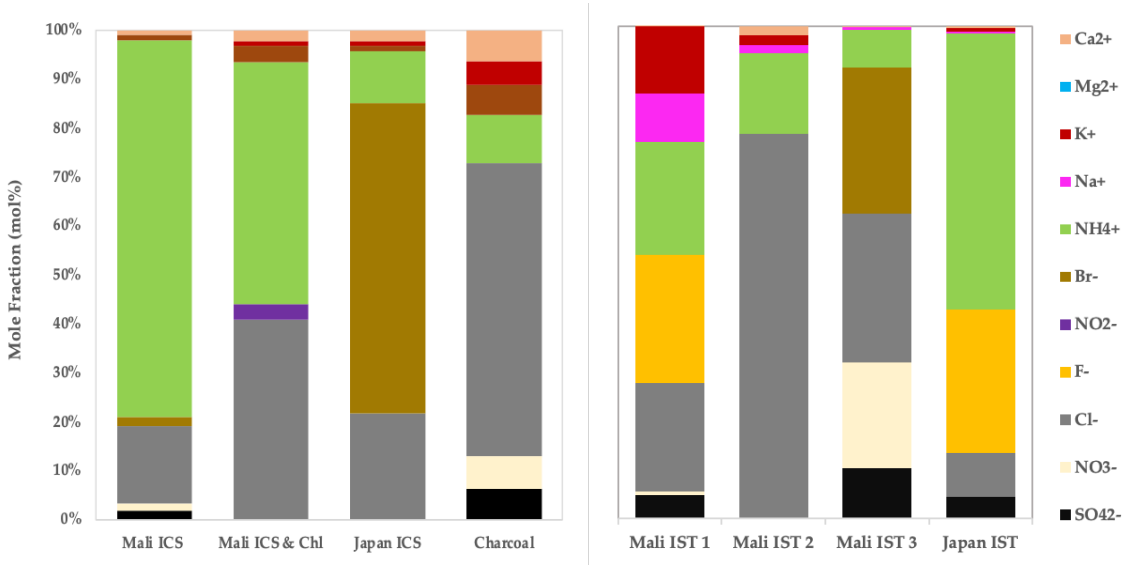
Cooking using wood as cooking fuel was $K^+ > Cl^- > Ca^{2+} > F^- > SO_4^{2-} > Mg^{2+} > NO_3^- >$

$NH_4^+ > Na^+$. K^+ accounted for 32 mol%, Cl^- and Ca^{2+} both accounted 20 mol%. Cl^- showed a minor contribution for charcoal fuel compared to the wood fuel. And, Na^+ showed a high contribution for charcoal fuel but minor for wood fuel. K^+ and Ca^{2+} were significant in both samples. K^+ is known as one the main ions detected during biomass combustion especially for wood combustion. Ca^{2+} and Na^+ have also been reported from biomass burning. The presence of Cl^- in the wood cooking sample might be associated with biomass burning and cooking. Cl^- have also been detected from cooking vegetables with high chlorine content such as garlic and onions [108] [109] [110].

The order for incense samples was F^- (50 mol%), NH_4^+ (21 mol%) and Cl^- (13 mol%). The order of the ions was $F > NH_4^+ > Cl^- > K^+$ $Ca^{2+} > Na^+ > NO_3^- > Mg^{2+} > SO_4^{2-}$. F^-, NH_4^+ and Cl^- represented 50 mol%, 21 mol% and 13 mol% respectively. Insecticide samples were predominant in anion and cation; F^- (28 mol%), Ca^{2+} (22 mol%) and K^+ (14 mol%). The order of the ions was $F^- > K^+ > SO_4^{2-} > Mg^{2+} > NH_4^+ > NO_3^- > Na^+ > Br^- > NO_2{}^-$. F^- was identified as a main product from biomass burning [10]. The high percentage F^- in both (insecticide and incense) can be attributed to their biomass content. The main ingredient of traditional made incense in Mali is wood residues or tree roots impregnated in perfumes. Insecticides (mosquito coils) are wood based [111]. Higher F^- ion contribution was observed in ICS and IST compared to cooking samples (with charcoal and wood as cooking fuel). This suggest that even though the high percentage of F^- in both products (incense and insecticide) might be a result of their biomass content, F^- might also be a specific to ICS and IST products.

Figure 3.12 represent the ionic composition of three most popular Malian insecticides (IST1 to IST3 for the most to least popular), a typical Japanese insecticide, Malian traditional incense and Japanese incense stick. Figure 3.12a and Figure 3.12b respectively for ICS and IST.

In Bamako like in many other cities incense is combusted using charcoal. Therefore, the combustion experiment included incense samples without charcoal and incense samples mixed with charcoal. Both Malian and Japanese incense were significantly loaded with Cl^-; 16 mol%



(a) Incense **(b)** Insecticide

Figure 3.12: Ion composition comparison Japanese products and Malian products. ICS: Incense, IST: Insecticide, CHL: Charcoal

and 22 mol% respectively. Cl^- was also significantly present in the ICS samples collected in Bamako (Figure 3.11). Cl^- was identified as one of the main compounds in different ICS samples (Kim Oanh, 2020). The dominant species in Malian incense was NH_4^+ and presented 77 mol% (Figure 2a). The contribution of NH_4^+ (Figure 1) in the in-situ samples was lower but significant (21 mol%). After mixing the samples with charcoal, the contribution of NH_4^+ ions decreased to 50 mol% and Cl^- increased from 16 to 41 mol%. The the simultaneous combustion of incense and charcoal might have decreased the quantity of ICS sample combusted; resulting in a decrease of NH_4^+ compared to the combustion of only ICS. And, the addition of charcoal might have increased the Cl^- contribution. In fact, charcoal was dominated with Cl^-. Japanese ICS showed a different ionic composition with a dominance in Br^- ion (63 mol%) reported from biomass burning, followed by Cl^- (22 mol%) and NH_4^+ (11%). The ionic contribution was different for different IST brands but, Cl^- and NH_4^+ were detected in all the samples. Cl^- had a larger contribution for Malian IST while NH_4^+ had a lager contribution for Japanese IST. These ions might also be specific to ICS and IST products [109] [112] [113]. Mali IST1 and Japan IST seemed to have similar ionic composition as they shared the particularity of emitting F^- ion which might be liberated from a specific ingredient in these IST. The samples collected in Bamako also showed a high contribution in F^-. As a matter of fact, IST1 was the most popular

brand in Bamako city. This might be the reason why in situ IST samples showed a significant F^- contribution. Furthermore, F^- was not detected in ICS combustion experiment but was highly loaded in the in-situ ICS samples (28 mol %). This can be explained by the fact that ICS is burned in traditional clay burner in Bamako (Figure 2.11a). F^- is naturally abundant in clay. It was highly detected from clay combustion experiments in previous studies [114] [115]. Br^- was detected only in Mali IST3 and had a significant contribution (30 mol%).

Ca^{2+} is mostly associated with soil or crustal sources, its contribution was significant for nearly all the emission sources in Bamako but low for the combustion experiment. This suggests that in addition to Ca^{2+} from biomass combustion, the outdoor dust re-suspension might affect the air quality in households' micro-environments in Bamako.

- **Ion equivalent**

The acidity-alkalinity analysis of particles indicates the acid base balance of ions in particles [116] [117]. Cooking samples showed an alkaline stage due to the high loading in cation. On the other hand, IST and ICS were highly loaded in anion and revealed an acidic stage (Table 3.7). Acidic ions have been linked to negative health effects [118] [119].

Table 3.7: Ionic balance for different household emission sources

	A/C acidic	A/C alkaline
Charcoal cooking		0.31
Wood cooking		0.29
Incense	1.22	
Insecticide	1.62	

Carbonaceous composition

OC is either directly emitted from primary sources or produced from secondary atmospheric reactions of gaseous organic precursors. EC is mainly formed from incomplete fuel combustion at high temperatures [120]. Numerous researches worldwide identified activities such biomass combustion (wood, leaves, charcoal) and motor vehicles emissions as the main sources of OC

and EC [121][122]. In this study, the combustion of ICS and IST presented relatively higher values compared to the cooking activity using charcoal or wood (Figure 3.13).

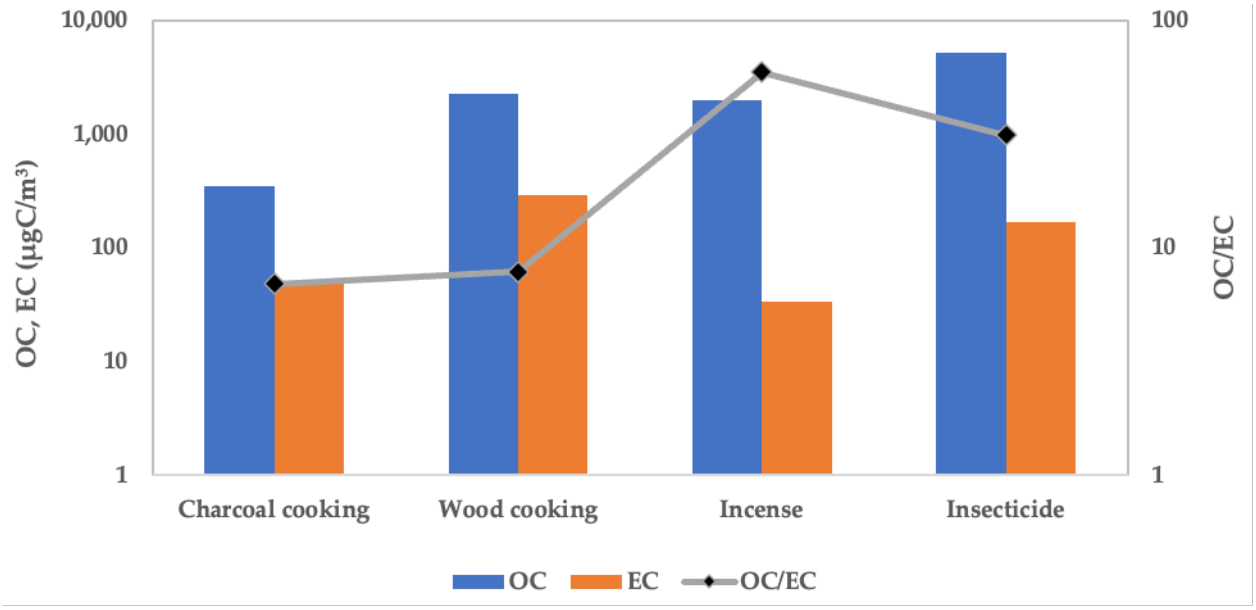
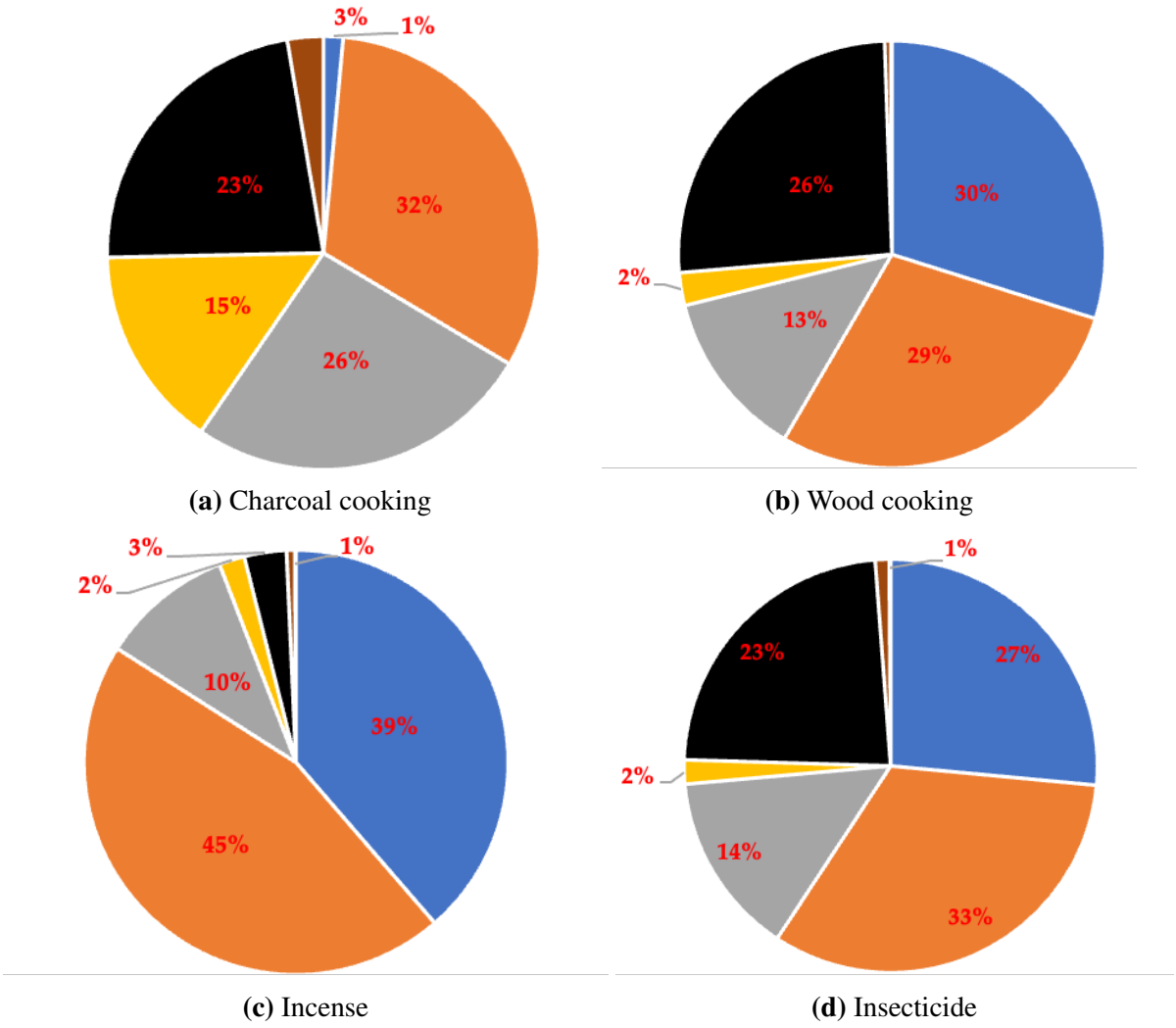


Figure 3.13: Total OC, total EC and OC/EC at different sampling sources

OC accounted for the largest fraction of carbonaceous in household samples (Figure 3.14). With the largest contribution during the combustion of ICS and IST (96 and 75%). Charcoal and wood cooking were 75 and 74% respectively. This suggest that although emissions sources differed, they had the common characteristic of containing high volatile compounds. Similarly, OC was the dominant carbonaceous for the combustion experiments.

Biomass burning including household fuel combustion is a major source of carbonaceous. This emits higher OC than EC. In the present study, the OC/EC ratio largely fluctuated from an emission source to another (Figure 3.13). The highest ratios were observed in the households' indoor microenvironments. 59 and 30 respectively for ICS and IST. This may be due to the smoldering combustion type of the products; which is characterized by a high OC/EC ratio [123] [124]. The cooking activity with charcoal and wood fuel presented much lower ratios; 7 and 8 respectively. Compared to other studies, the average ratio from wood cooking was higher than the average values reported by He et al, (1.24 to 5.26), Atiku et al, (0.41 to 1.46),



(a) Charcoal cooking

(b) Wood cooking

(c) Incense

(d) Insecticide

Figure 3.14: Contribution of the different fractions of OC and EC. OC1 (blue); OC2 (orange), OC3 (grey); OC4 (yellow); EC1 (black); EC2 (brown); EC3 (purple)

Popovicheva et al, (4.1 to 4.3) and lower than values reported by Coffey et al, (14 to 15) Keita et al, (12.7), Popovicheva et al (12.3). The difference in wood quality and species combined with the difference in combustion conditions could have resulted to high variability in the ratio obtained from different studies. A lower value (2.7) for charcoal has been reported by Keita et al [125] [126] [38] [127] [128] [129].

- **Characterization of different fractions of OC and EC**

Figure 3.15 illustrates different OC and EC fraction for different emission sources.

The samples were characterized by a higher fraction of OC1 and OC2 except for charcoal

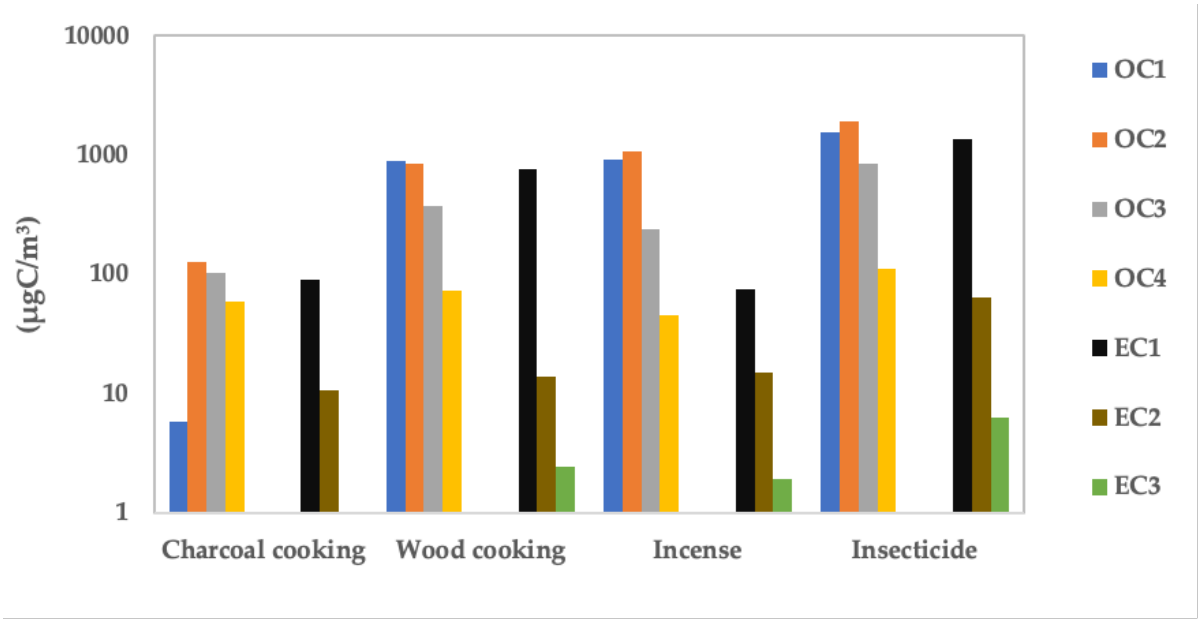


Figure 3.15: Different carbon fractions OC1, OC2, OC3, OC4 and EC1, EC2, EC3 in different samples.

cooking. Presenting OC2 as the highest fraction but OC1 as the lowest. OC1 and OC2 indicate high content of volatile organic compounds and were associated with biomass burning [130] [131] [132] [133].. OC3, indicating dust resuspension and biomass combustion also presented high values [134] [132] [135] [136]. OC4 was the lowest for IST, ICS and wood cooking. EC1 was the dominant fraction of EC in all samples and is usually associated to biomass burning. OC2, OC3 and EC2 indicate coal combustion [130] [137] [133].

Additionally, Figure 3.16 shows char EC, soot EC and char EC/soot EC ratio. Char-EC which is characterized by incomplete combustion was obtained by subtracting POC (Pyrolyzed Organic Carbon) value from EC1 value. Soot EC; characterized by high temperature combustion was calculated as the sum of EC2 and EC3. Char EC/soot EC is a good indicator of biomass burning and incomplete combustion [138] [139] [140].

Previous studies presented high char EC in samples collected near biomass combustion sites and traffic sites. The ratio char EC /Soot EC varied for different emission sources. Char EC/soot EC was reported to be 6.0 ± 4.6 and 4.8 ± 2.2 for biomass burning, 4.3 ± 1.9 and 1.3 ± 0.8 for coal combustion [138]. In this study, the highest ratio was observed in wood combustion (19.6),

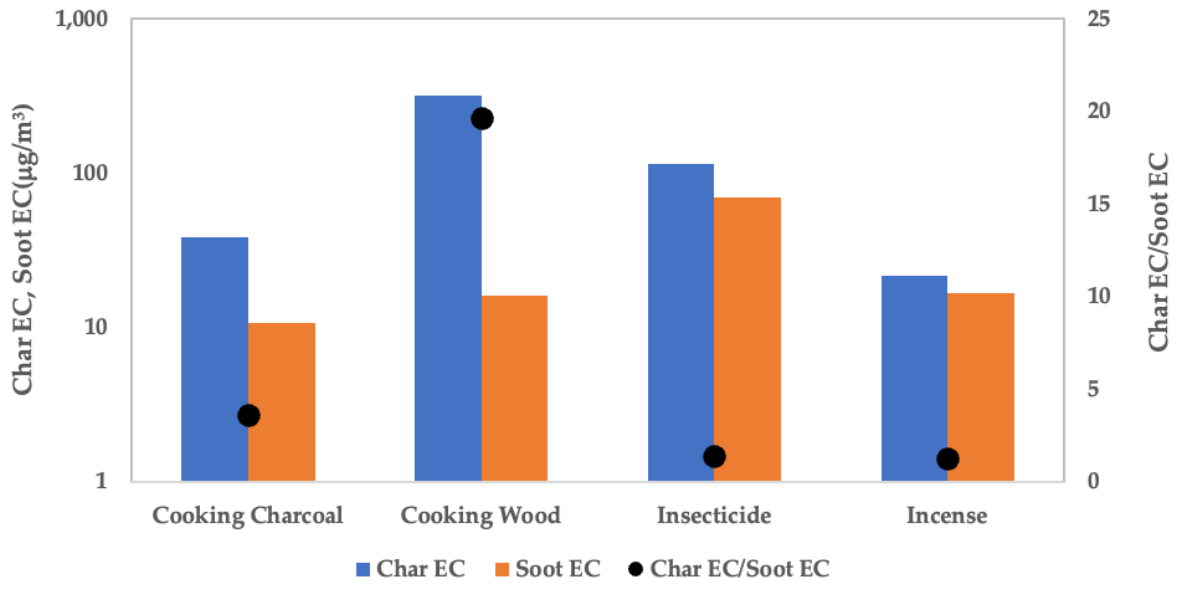


Figure 3.16: Char EC, Soot EC and Char EC/Soot EC for different emission sources

followed by charcoal (3.6) and IST (1.6) and ICS (1.4). Cooking stoves used in Bamako are not adapted for efficient combustion; resulting in smoldering. And, the moldering combustion of biomass results in high char EC/soot EC [141]. Our results presented higher char EC in all samples. This suggest that all the emission sources were characterized by incomplete combustion.

PM metal composition

In general, the same constituents were detected for the four emission sources with a slightly different distribution (Figure 3.17). K, Al and Fe were the dominant constituents. K, a well-known biomass tracer was highly detected in the samples. IST presented the highest contribution followed by wood cooking, ICS and charcoal cooking. Al and Fe were also dominant for all emission sources with ICS and charcoal cooking presenting the highest contribution. Wood and IST presented lower contribution. Ca and Mg were more abundant in charcoal cooking followed by ICS, wood cooking and IST. Zn and Na were also detected for all the emission sources. Other metals (Mn, Rb, Ba) had negligible contributions. Al, Fe, Mg, Ca and Na are dust tracers and were detected in previous studies during biomass combustion and from cooking fumes [142].

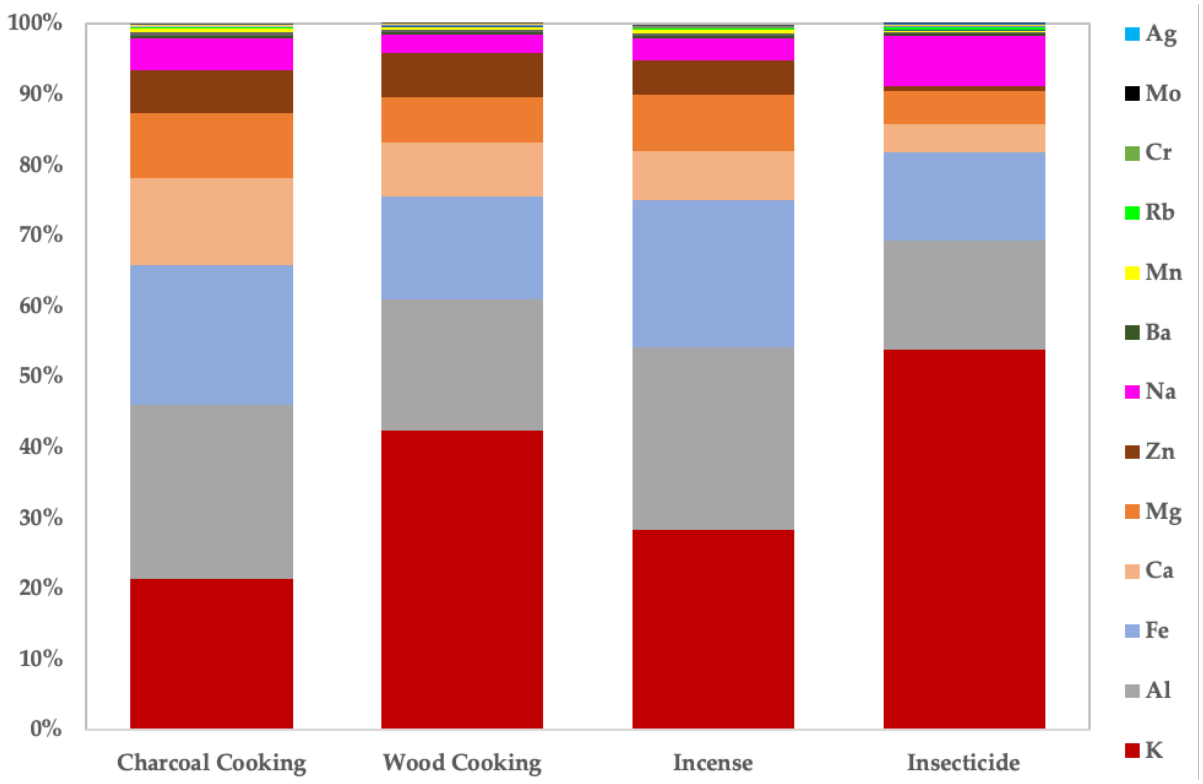
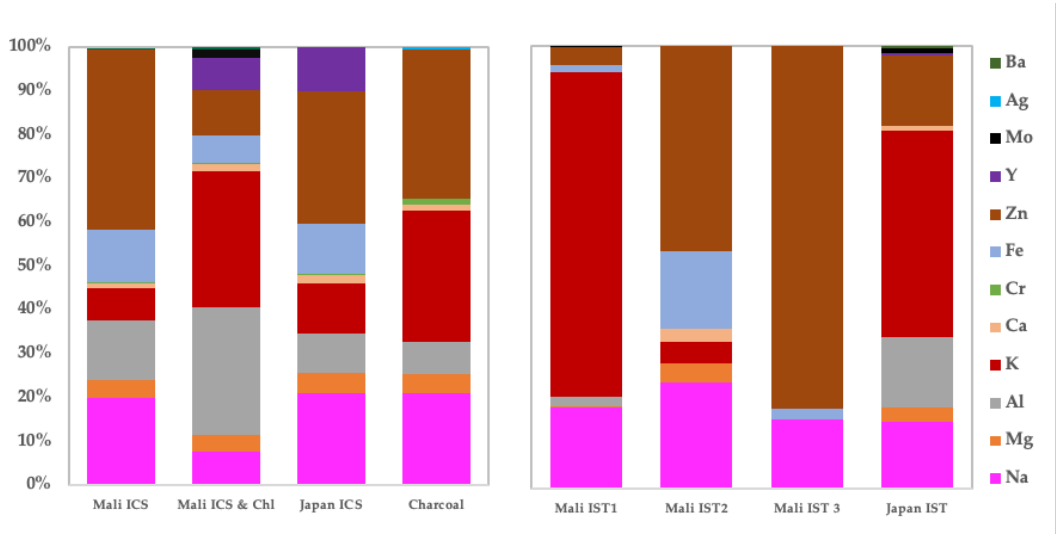


Figure 3.17: Metal composition for different household combustion sources

Zinc (Zn) which is a volatile metal had a low contribution for the ICS and IST collected in Bamako but, was the predominant element for the ICS and IST samples collected during the combustion experiment [143]. Malian IST; especially IST2 and IST3 were highly loaded with Zn (Figure 3.18). The higher contribution of this metal in the combustion experiment samples compared to the in-situ samples might be due to its physical properties and the difference in the sampling conditions. The limited oxygen concentration during the combustion experiment was favorable for the devolatilization of Zn. Which might have been directly sampled upon liberation. Whereas for the in-situ sampling condition was less favorable for devolatilization and more favorable for diffusion.

IST1 and Japanese IST seemed to be the closed concerning the metallic constituents' distribution. IST1 was dominated by K. Japanese IST was dominated by K and had also a considerable amount of Zn, Na, and Al. The combustion of ICS using charcoal presented higher concentration in Al and Zn and a lower Na compared to the combustion with no charcoal. Na



(a) Incense **(b)** Insecticide

Figure 3.18: Metal composition comparison; Japanese products and Malian products. ICS: Incense, IST: Insecticide, ICSChl: Incense and Charcoal

was detected in all samples (in-situ and the combustion experiment). And, had a significant contribution for both Malian and Japanese products. This suggest that Na might be emitted from the ingredients used in these products. Na was previously detected from the combustion of similar products due to the addition $NaNO_3$ as oxidizer to facilitate the combustion [144]. Dust tracers (Ca and Mg) had higher contribution in the samples collected in households compared to the combustion experiment samples. This suggests once more the influence of outdoor dust resuspension on the indoor air quality in Bamako.

3.2.2 Health exposure assessment

In this study, the concentration of 35 metals were determined for different emission sources. The average concentrations (in ng/m^3) are reported in Table A.3 and Figure 3.19. Except for a few metals (Ni, Ti, Bi, U, Mo), cooking with wood samples presented the highest metal concentrations. The most dominant metals were K, Al, Fe, Ca, Mg, Zn and Na among which biomass combustion tracers, soil dust resuspension tracers and traffic indicators.

PM emitted in the atmosphere can trigger human health. They can enter the organisms through diverse pathways. The main exposure occurs during the respiratory process. Inhaled

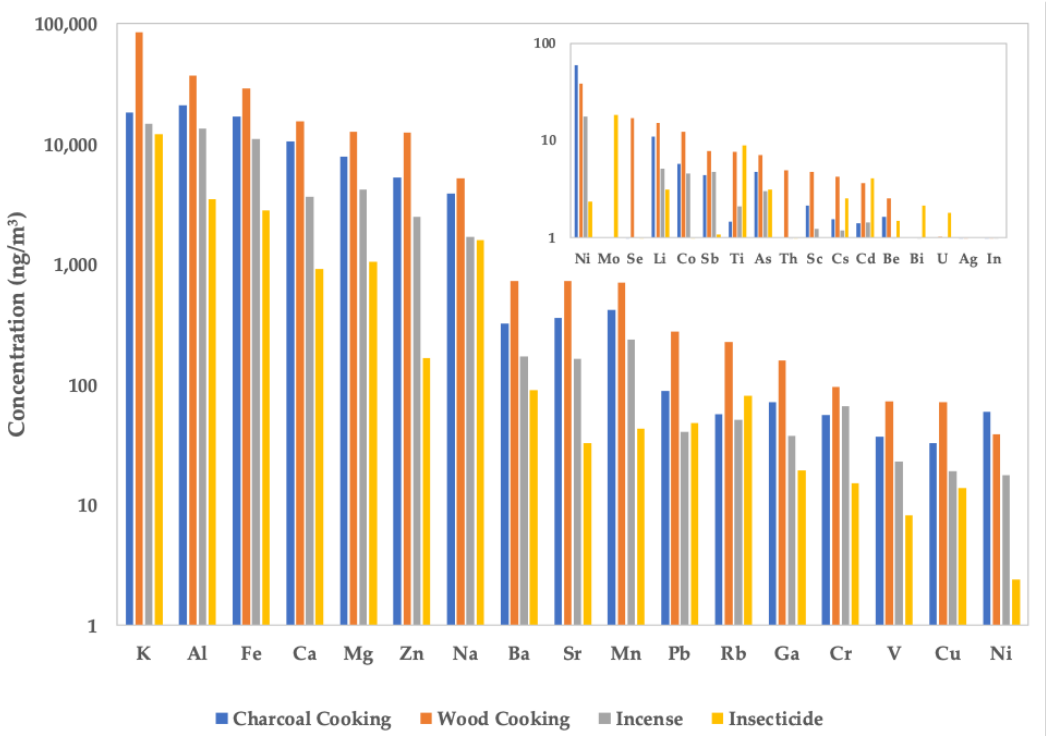


Figure 3.19: Concentration of heavy metals for different emission sources

PM can deposit in the deepest body systems including respiratory, cardiovascular, nervous and circulatory systems where; they can cause great damages. Hence, in this study, we estimated the health risks from PM exposure via the inhalation route. The HQ for a single heavy metal and HI for multiple heavy metals were calculated to estimate the potential non-carcinogenic health impacts caused by the exposure to a single heavy metal or a mixture of heavy metals respectively. CR was calculated to estimate the carcinogenic risks. Similarly to the non-carcinogenic risks, CR was evaluated for a single metal as well as T-CR (total CR) for multiple metals.

- **Non-carcinogenic risks**

Table 3.8 presents the HQ and HI for adults and children (estimation method; page 44-45). In this research, HQ and HI were estimated for different typical daily household activities. The HQ for Mn exceeded the recommend exposure limit for the cooking activity using wood in adults and children. Ni presented unsafe values in children for the cooking activity (with both charcoal and wood) and, the use of ICS.

The hazard index exceed the safe exposure limit of 1 in adults and children except for the use

Table 3.8: Non-carcinogenic risks of toxic metals for adults and children. Charcoal: charcoal cooking, Wood: Wood cooking, IST: Insecticides; ICS: Incense, Adl:adult, Chl: Children.

	Charcoal		**Wood**		**Icense**		**Insecticide**	
	Adl	Chl	Adl	Chl	Adl	Chl	Adl	Chl
Cr	0.07	0.07	0.11	0.11	0.10	0.10	0.02	0.02
Mn	0.99	0.99	1.68	1.68	0.70	0.70	0.13	0.13
Ni	0.48	4.91	0.31	3.16	0.18	1.82	0.2	0.25
As	0.04	0.04	0.06	0.06	0.03	0.03	0.03	0.03
Cd	0.02	0.02	0.04	0.04	0.02	0.02	0.06	0.06
Be	0.02	0.02	0.10	0.03	0.08	0.01	0.08	0.02
HI	1.61	6.04	2.31	5.09	1.11	2.69	0.35	0.51

of IST. The cooking activity represented the greatest risk in both (adults and children) followed by ICS and IST. In this study, HI was higher in children compared to adults.

- **Carcinogenic risks**

Table 3.9 indicates the carcinogenic risk in adults and children (estimation method; page 45-46). The CR exceed the safe exposure limit for all the household emission sources in adults and children. The highest toxicity was attributed to cooking using wood followed by the use of ICS, cooking using charcoal, traffic and the use of IST. Children are considered as sensitive people. Due to their young age, there are more vulnerable. Nevertheless, in this research, the carcinogenic risk was higher in children compared to adults. Cooking using wood fuel and the combustion of ICS in households presented unacceptable CR values of 1.45E0-4 and 1.21E-04 respectively.

In general, CR values were below the unacceptable level but above the lower safe exposure limit for all the emission sources. Although the samples were not dominated by toxic metals, the health risk assessment study indicated possible adverse effects on human health. This implies that even though the toxic metals concentrations were low compared to the non-toxic ones, repeated exposure and the exposure duration can trigger health.

Moreover, the risks from the exposure to ambient PM collected at a typical roadside were determined in the following section. The exposure risks were lower compared to the risks from

Table 3.9: Carcinogenic risks of toxic metals for adults and children. Charcoal: charcoal cooking, Wood: Wood cooking, Adl:adult, Chl: Children, T-CR: Total Carcinogenic Risk

	Charcoal		**Wood**		**Incense**		**Insecticide**	
	Adl	Chl	Adl	Chl	Adl	Chl	Adl	Chl
Cr	2.76E-05	8.04E-05	4.70E-05	1.37E-04	4.04E-05	1.18E-04	9.28E-06	2.71E-05
Ni	5.87E-07	1.71E-06	3.78E-07	1.10E-06	2.18E-07	6.35E-07	2.95E-08	8.60E-08
As	8.46E-07	2.47E-06	1.25E-06	3.64E-06	6.69E-07	1.19E-06	6.94E-07	2.02E-06
Cd	1.06E-07	3.09E-07	2.73E-07	7.96E-07	1.34E-07	3.89E-07	3.78E-07	1.10E-06
Pb	4.34E-08	1.27E-07	1.35E-07	3.95E-07	2.94E-08	7.26E-08	2.49E-08	8.56E-08
Be	6.08E-06	9.97E-07	6.85E-06	1.52E-06	3.87E-06	1.10E-07	3.86E-06	1.13E-06
T-CR	3.52E-05	8.60E-05	5.59E-05	1.45E-04	4.53E-05	1.21E-04	1.43E-05	3.15E-05

the households' typical activities. Except the use of IST, all the household's emission sources presented a greater non-carcinogenic and carcinogenic risk compared to the roadside (Table 3.10). We spend most of our time in indoor microenvironments. Indoor microenvironments are generally perceived to be a safer microenvironments compared to the outdoor microenvironments. But indoor pollution can be higher than what we sometimes believe. This highlights the elevated risk from the exposure to indoor air pollutants. In general, the risks in the households in this study were higher compared to the values reported by Yang et al. 2014, Yaparla et al., 2019 and Embiale et al., 2020 respectively in Chinese, Indian and Ethiopian household microenvironments. But, the CR was lower; 3.35E-04 in adults and 8.38E-5 in children (Table 3.10) [145] [146] [147]. Outdoor PM exposure has been extensively investigated compared to the indoor PM exposure. These results suggested that the indoor PM exposure causes a greater treat than thew outdoor PM exposure. Hence, more attention should be paid to the PM exposure in indoor microenvironments especially during typical daily activities. Furthermore, most researches focus on either indoor exposure risk or outdoor exposure risks. However, simultaneously evaluating both; indoor and outdoor risks is necessary to provide utter information on the health risks from the exposure to air pollution.

Table 3.10: Non-carcinogenic and carcinogenic risks of toxic metals for adults and children in this research and previous researches. Numbers in [] are references. CHL: charcoal cooking, Wood: Wood cooking, N-gas: Natural gas for cooking, Smkg: smoking, Rds: Roadside, amb: ambient air , LPG: Liquefied petroleum gas, Adl:adult, Chl: Children, HI: Hazard Index, T-CR: Total Carcinogenic Risk

Non-carcinogenic risks (HI)												
	This research, 2022		**China [145]**		**India [146]**		**Ethiopia [147]**		**China [55]**		**Japan [148]**	
	Adl	Chl	Adl	Chl	Adl	Chl	Adl	Chl	Adl	Chl	Adl	Chl
CHL	1.61	6.04					0.03	0.046				
Wood	2.31	5.09										
Kerosene							0.145	0.223				
electricity							0.022	0.033				
N-gas/smkg			2.55	2.55								
Biomass					4.32E-04	8.17E-04						
LPG					5.62E-04	1.03E-03						
ICS	1.11	2.69										
IST	0.35	0.51										
Rds/amb	0.55	1.35							1.38	1.38	0.2	0.2
Carcinogenic risks (T-CR)												
CHL	3.52E-05	8.60E-05					1.95E-7	3.61E-08				
Wood	5.59E-05	1.45E-04										
Kerosene							6.40E-07	1.18E-07				
electricity							1.45E-07	2.67E-8				
N-gas/smkg			3.35-04	8.38E-05								
Biomass					5.55E-09	2.62E-09						
LPG					4.11E-09	1.95E-09						
ICS	4.53E-05	1.21E-04										
IST	1.43E-05	3.15E-05										
Rds/amb	2.63E-05	7.51E-05							1.90E-05	4.80E-06	2.5E-05	6.24E-06

- **Possible health risks from literature review**

PM size is an essential parameter in evaluating its exposure risks. Those emitted from combustion sources usually have a large fine fraction [149] [150]. Studies suggested that fine PM causes the greatest health issues. This fraction, once inhaled can easily reach the deepest human body systems where, they have a higher deposition surface area [151] [78]. In addition to the size, the chemical composition is a very important characteristic that provides more information on the effects. In this study, we also characterized the possible health risks from the exposure to different PM chemical constituents by comparing our results to previous researches. Table 3.11 presents the values from this research as well as the values reported from previous researches. Epidemiological and toxicological studies have investigated the relationship between the PM chemical components and health risks. Adverse effects were commonly observed from the exposure to carbonaceous compounds, ionic compounds such as SO_4^{2-}, NO_3^-, NH_4^+ and metals such as Cu, Zn, Ni. OC and EC were often identified as the components with the highest morbidity and mortality risks over different regions [151] [152] [153]. OC was strongly related to cardiovascular mortality. Significant correlations were found between EC and a higher risk of ischemic heart disease and respiratory mortality [154]. SO_4^{2-} and NH_4^+ and NO_3^- were associated with vascular effects [155] [156]. Ni was significantly associated with acute heart rate and Cu was correlated to heart disease and respiratory mortality [157] [154]. Our resulted presented very high carbonaceous concentration from the households' combustion sources. OC emitted from cooking activities was 2271.4 and 346.2 μgC/m^3 for wood and charcoal cooking respectively and, EC was 290.5 and 50.2 μgC/m^3. IST concentration presented values of 5172.5 μgC/m^3 (OC) and 188.2 μgC/m^3 (EC) in average. And, 1972.3 μgC/m^3(OC) and 33.43 μgC/m^3 (EC) for ICS. These high concentrations might be attributed to the indoor combustion with low aeration conditions. As a matter of fact, high OC (up to 3802 μg/m^3) and EC (up to 203 μg/m^3) were previously reported from biomass burning [128]. Alves et al.2011, reported very high values from various cooking types. OC was up to 62 mg/m^3 and EC 7.5 mg/m^3 for charcoal grilling cooking. Wood oven presented higher OC (178 mg/m^3) and EC (9.24 mg/m^3) [158]. This demonstrates that the emission of carbonaceous compounds can fluctuate depending on the combustion conditions (including fuel type and aeration conditions).

Previous epidemiological and toxicological studies reported health risks due to the exposure to much lower OC and EC concentration compared to the ones measured in this study. These studies have also linked health risks to certain ionic and metal constituents. The exposure to OC (3.8-5 $\mu g/m^3$), EC (0.7-1.9 $\mu g/m^3$), SO_4^{2-} (5.6-6.9 $\mu g/m^3$), NO_3^- (1.8-4.7 $\mu g/m^3$) and metals Pb, Ni, Cu at concentrations ranging from 1.9 to 28.9 ng/m^3 were associated with daily respiratory diseases (2-9 cases), cardiovascular diseases (3-21 cases) and mortality (12-104 death) over six different cities in South Korea from 2013 to 2015 [152]. The highest daily morbidity and mortality were observed in cities with the highest concentrations of the components. Michikawa et al. associated OC (3.9 $\mu g/m^3$) and EC (2.6 $\mu g/m^3$) with an increase in mortality in Tokyo, Japan over 4 years [159]. Similarly, in China, Guangzhou the exposure to a concentration of 5.4 $\mu g/m^3$ for OC and 2.8 $\mu g/m^3$ for EC over 4 years was associated with mortality risks [160]. In Shanghai, China, the effects of 5 major PM constituents OC, EC, SO_4^{2-}, NH_4^+, NO_3^- were investigated. The average concentrations over 2 years were 6.5, 3.8, 20, 7.6, 10.8 $\mu g/m^3$ respectively. The increment in these constituents' concentrations of 10 $\mu g/m^3$ resulted to the increase of respiratory disease mortality and circulatory disease mortality risks. With the highest risk attributed to EC (44.99%). Followed by OC (10.40%), NH_4^+ (7.34%) and NO_3^- (5,34%). In addition, EC contributed to 10. 48% of all causes of mortality associated to PM exposure [161]. Atkinson et al. 2015 also reported that an increase of 1 $\mu g/m^3$ in EC concentration was associated with an increase of 1.30% of mortality (respiratory and cardiovascular) over different region; US, Chilie, China and South Korea; in line with the results presented by Wang et al. 2019 [162]. In this study the OC and EC concentration were 100 times higher than the values reported in the aforementioned studies. The extremely high observed concentrations present very acute morbidity and mortality risks in Bamako's inhabitants. Average SO_4^{2-} (14.8 $\mu g/m^3$), NH_4^+ (8.9 $\mu g/m^3$), NO_3^- (13.5 $\mu g/m^3$) concentration over 2 years were associated with an increase of mortality from cardiovascular diseases, stroke, ischemic heart disease, respiratory diseases and chronic obstructive pulmonary diseases in China [163]. Li et al. found a relationship between NO_3^- (6.3 $\mu g/m^3$ on 4 years average exposure) and endocrine diseases (that affects hormones) and neoplasms (tumors) [160]. Also, Liu et al reported that SO_4^{2-} (13.65 $\mu g/m^3$), NH_4^+ (6.4 $\mu g/m^3$) and NO_3^- (9.41 $\mu g/m^3$) had an effect on blood inflammation and coagulation

which can result in damages in organs, strokes, heart attacks and even death [155]. Compared to these studies, our results presented higher ionic compounds concentrations during typical activities. SO_4^{2-} was 17.16, 3.28, 40.41 and 10.90 $\mu g/m^3$ for the use of ICS, IST, wood cooking and charcoal cooking respectively. SO_4^{2-} values were higher in this studies except for IST but, IST presented a higher NH_4^+ concentration (21.15 $\mu g/m^3$). However, both SO_4^{2-} and NH_4^+ are risk factors for blood clot and blood infection. Plus, NO_3^- values were higher than the values associated with hormonal problems and tumor except for IST.

In this study, similarly to many others, biomass burning emitted high carbonaceous components, especially the OC fraction. PAHs constitute a large fraction of OC and have mutagenic and carcinogenic effects. Alves and colleagues reported that average concentration of OC (10.66 $\mu g/m^3$) and EC (0.99 $\mu g/m^3$) from biomass burning during the dry season 2015 in Porto Velho, western Amazon resulted in an excess of cancer risk [164]. And, Kim et al. reported an increase in cancer mortality within 4 years period strongly associated with mean concentration of OC (3.09 $\mu g/m^3$) and EC (0.47 $\mu g/m^3$) from 2003 to 2007 in Denver metropolitan region [153]. Furthermore, Jenwitheesuk et al. suggested that an increase of 1 $\mu g/m^3$ in OC concentration increases the risk of lung cancer by 21% [165]. These values are much lower than the values recorded in households' microenvironments in Bamako. This clearly suggests that the risks of the above-mentioned health problems and their consequences is very high in the inhabitants.

The repetitive exposure increases the relative risks from the exposure to PM constituents [161]. Nevertheless, the exposure sources were part of the daily common activities. This emphasizes the high risk that the inhabitants are facing from the exposure to PM in the household microenvironments. Therefore, it is important to implement strict measures for the population's health safety improvement in Bamako.

Table 3.11: PM constituents concentration in this research and previous researches. Numbers in [] are references. Emission sources are in italic letters. CHL: charcoal cooking, Wood: Wood cooking, ICS: incense, IST: insecticide, Rds: Roadside, amb: ambient air , OC: organic Carbon, EC: elemental Carbon, SO_4^{2-}: sulfate, NO_3^-: nitrate, NH_4^+: ammonium. All values are in $\mu g/m^3$

		OC	EC	SO_4^{2-}	NO_3^-	NH_4^+	Pb	Ni	Cu
This research (2022)	*CHL*	346.6	50.2	10.90	7.25	1.75	0.08	0.059	0.03.2
	Wood	2271.4	290.5	40.41	17.81	3.76	0.27	0.038	0.071
	ICS	1972.3	33.43	17.16	6.67	2.51	0.04	0.017	0.019
	IST	5172.5	188.2	3.28	3.48	21.15	0.047	0.002	0.013
	Rds/amd	28.03	5.82	2.09	1.41	0.2	0.02	0.016	0.027
[128] North Vietnam	*B burning*	3802	203						
[158] Amazon region	*CHL grilling*	62000	350						
[158] Amazon region	*Wood oven*	178000	9240						
[152] 6 different cities	*Rds/amb*	3.5-5	0.7-1.9	5.6-6.9		1.8-4.7	0.022-0.029	0.002-0.004	0.006-0.008
[159] Japan, Tokyo	*Rds/amb*	3.9	2.6						
[160] China, Guangzhou	*Rds/amb*	5.4	2.8		6.3				
[161] China, Shanghai	*Rds/amb*	6.5	3.8	20	10.8	7.6			
[163] China	*Rds/amb*			14.8	13.5	8.9			
[155] China, Shanghai	*Rds/amb (in-vivo)*			13.65	9.41	6.4			
[164] Porto Velho	*Rds/amb*	10	0.99						
[153] Denver metropolitan region	*Rds/amb*	3.09	0.47	1.08	1.03				

3.2.3 Conclusion

In this study, the composition of PM from specific households emission sources were characterized. Cooking the use of ICS and IST were previously identified as the most personal exposure sources in households [100]. Samples were collected on filters in Bamako city and in the ACAP laboratory.

The results indicated that the distribution of the elements significantly varied from an emission source to another. The different characteristics observed for different microenvironments marked the exposure. The ion distribution varied from. ICS and IST were acidic and the cooking samples were alkaline. OC was the dominant carbonaceous. The char EC/soot EC indicated that the emission sources were mainly characterized by incomplete combustion of biomass contents. The metal composition was prevalent in biomass and dust tracers. The health risk assessment study indicated that the exposure to PM was unsafe. HI varied between 0.35 to 6.04. IST presented a value below the HI limit of 1 in adults and children. On the other hand, the values exceeded the safety limit for cooking and the use of ICS. CR exceeded the lower limit of exposure of 1E-6 for all activities and microenvironments but, were below the unacceptable level of 1E-4. The cancer risk was higher in adults than children. In general, the cooking activity had the highest health risks, followed by the use of ICS and IST. The comparison between Japanese and Malian products indicated that the mass percentage of the elements were different. The dominant ion in Malian ICS was NH_4^+ and, Br^- for the Japanese one. Except for the Japanese ICS, EC had no or a negligeable contribution to the carbonaceous components. K, Zn, Na and Al were dominant metals in ICS and IST samples. Our experiment showed that different IST brands have different composition. In addition, the burning condition might have had an influence on the liberated elements from the IST and ICS.

The findings from this study indicated that it is crucially important to control the household the emission sources. Both local government and inhabitants should participate in this effort. Exposure from cooking is a very important issue. Gradually switching from the inefficient cooking stoves to the use of improved cooking stoves could considerably reduce the exposure.

Incense combustion is an important part of the culture and the use of insecticides is a very common practice in Bamako to prevent malaria. Both ICS and IST are combusted indoors where, the air exchange is very limited. Make sure the room aeration is adequate during the use of IST and ICS and, reducing the frequency of use could be a good way to reduce the exposure. Moreover, previous studies have reported that mosquito coils might be inefficient to prevent malaria and have harmful effects. According to Hogarh et al, mosquito coils only have 24 to 64% efficiency [102] [166] [167] [168]. Given that and the possible health risks; the use of mosquito nets would be the best way to protect health. The sanitation level including waste water, households waste is an important factor for mosquitoes' proliferation. Improving the waste management system and the gradual improvement of the infrastructure could contributing to reduce the pollution and mosquitoes' reproduction. Likewise, reduce exposure to PM and the risk of contracting malaria.

To our knowledge, this is the first study addressing PM chemical composition in relation to the population daily exposure from household emission sources. This study highlighted the need to initiate regular air pollution monitoring systems for health and environment safety. Furthermore, the results provided scientific data that are essential as preliminary step in promulgating air pollution mitigation strategies and, reducing the personal exposure.

Chemical characterization of particulate matter from a typical roadside in Western Sub-Saharan Africa

Air quality is a worldwide growing concern for health and environment. The increase of ubiquitous elements by natural processes or anthropogenic activities results in a bad air quality especially, in urban environments experiencing intense human activities. Numerous anthropogenic activities such as road traffic, industrial activities, construction activities, biomass and biofuel combustion contribute to worsen the air quality over urban cities. Major air pollutants including particulate matter (PM) are continuously emitted into atmosphere. This results in effects on the ground surface atmosphere that we breath. PM results in many adverse effects on our living environment including visibility reduction and climate change. They also highly affect our health. It is one of the most affecting pollutants to human [169]. Researches have proven that the exposure to PM is a factor increasing the mortality and the morbidity rate [78]. Adverse effects such as respiratory diseases, cardiovascular diseases and even cancers have been associated to PM exposure in previous researches. These effects can lead to lifetime disability or death. PM pollution is a global problem. In 2016, 4.2 million of death was attributed to outdoor PM pollution. Furthermore, the 2019 report of the global burden of disease revealed that 93 billion of DALYs and 6.4 million of premature death were attributed to PM. According to the WHO and the World Bank, low-income countries are the most vulnerable. The socioeconomically situation exposes the populations to outdoor air pollutants from the traffic emissions, dust resuspension, uncontrolled incineration fuel combustion [13] [24]. In Bamako, the capital of

Mali in west north Africa, the traffic sector is dominated by motorbikes and second-hand cars. These cars usually do not longer meet the air quality standards of the exporting countries [170]. This associated with the fuel quality and the underdeveloped infrastructure can lead to a substantial air pollution. In a previous study, we provided evidence that the level of fine particulate matter ($PM_{2.5}$) in the traffic sector were above the WHO standards in Bamako city. The daily average varied from 30 to 42 $\mu g/m^3$ [100]. The adverse effects from PM exposure not only depends on the concentration but also the exposure time and the chemical composition. Heavy metals are one of the PM components that can greatly affect human health. These elements are toxic and persistent. They can enter the food chain and bioaccumulated in organisms. Damages on important organs such as brain, lung, kidney, liver and, muscles have been associated to PM exposure [10] [106]. Therefore, it is important to investigate PM chemical composition and evaluate the possible health risks. The chemical composition is also useful to determine the sources and/or fate of the PM emitted into the atmosphere. This study was initiated to advance our understanding on the chemical composition and relative toxicity of particles originating from a typical roadside in western sub- Saharan Africa where; information on air pollution is very lax. The main objectives of this research were to:

- determine the chemical composition of PM emitted from activities producing the greatest exposure in Bamako city;
- evaluate the health risk from PM exposure and;
- identify the possible ambient PM source contributions.

To do so, we collected PM on quartz and polytetrafluoroethylene (PTFE) filters at and, analyzed the ionic composition, the carbonaceous (organic carbon and elemental carbon) and, the metal composition. Our study provided useful information on the chemical composition of PM emitted at a typical roadside and the associated health risks. Studies that provide information on air pollution can considerably contribute to the improvement of air quality. Such studies have proven necessary to implement policies and enforce laws in many countries. Hence, our findings could be very useful for the local government and institutions in their efforts to promulgate effective plans for the air pollution control and improve public health.

3.3 Roadside PM chemical composition characterization

The $PM_{2.5}$ daily average concentration at the roadside was 45.6 ± 14.9 $\mu g/m^3$. This was higher than the daily standards of 25 $\mu g/m^3$and 35 $\mu g/m^3$ provided by WHO and the EPA AQI respectively [107] [13]. The PM collected on filter were used to determine the ion, carbonaceous (OC, EC) and metal composition of particles at a typical road side in Western Sub-Saharan Africa.

3.3.1 Different chemical components

Ion composition

In this study the concentration of seven anions (SO_4^{2-}, NO_3^-, Cl^-, F^-, PO_4^-, NO_2^-, Br^-) and five cations (NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}) were determined for different emission sources. PO_4^- concentration was under the detection limit therefore, it was excluded from the analysis. Figure 3.20 shows the ionic distribution.

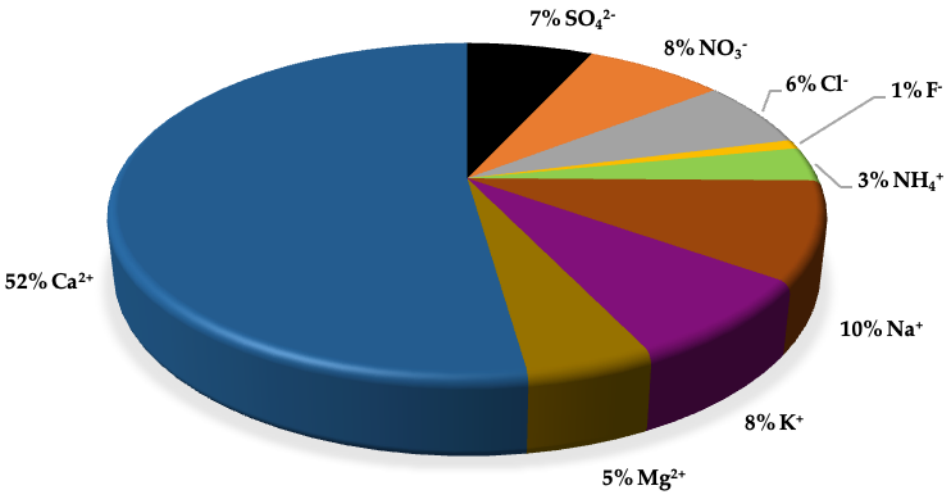


Figure 3.20: Ion composition in at a typical roadside in Bamako

The sampling site was dominated with cations. Predominant ions were Ca^{2+}, Na^+ and K^+. They respectively accounted for 52%, 10% and 8%. The order of the ion content was Ca^{2+}, $Na^+ > K^+ > NO_3^- > > SO_4^{2-} > Cl^- > Mg^{2+} > NH_4^+ > F^-$. Road side especially in developing countries are generally characterized by Ca^{2+} and Na^+ from dust re-suspension. The presence of K^+; associated with biomass burning can be attributed to street food preparation. NOx is usually

emitted from motor vehicles and SO_2 from biomass combustion or industries. $NO_3{}^-/SO_4^{2-}$ gives information on the influence of mobile and stationary sources to the air pollution. A ratio more than 1 indicates the dominance of mobile sources over stationary sources. And, less than 1 the dominance of stationary sources [171] [172]. The average ratio in this study was 1.1. Which, indicates the dominance of mobile sources such as motorbikes and cars.

- **Ion equivalent**

The acidity-alkalinity analysis of particles indicates the acid base balance of ions in particles [116] [117]. A value close to 1 suggests a neutral ionic stage; a value over 1 indicates an acidic stage and, a value below 1 indicates alkaline stage The ionic balance of the PM collected at the traffic site was 0.34. Therefore, were alkaline. Roadside was characterized with high dust re-suspension and dominated with of cations. This explains the alkaline stage.

Carbonaceous composition

Organic carbon (OC) and elemental carbon (EC) are the two main fractions that constitute the carbonaceous aerosols in the atmosphere. In this study we determined eight different carbon fractions (OC1, OC2, OC3, OC4, EC1, EC2, EC3, OP). Figure 3.21 presents the different OC and EC fractions. OC1 associated with biomass burning was the lowest. OC2 and OC3 were the most dominant fractions. These fractions indicate gasoline and coal combustion. OC4 fraction had a significant contribution and is largely associated with road dust. EC1 was the dominant fraction of EC and is usually high in motor vehicle emissions and road dust [132] [133]. EC2 and EC3 indicate diesel combustion and coal combustion [130] [137] [133]. EC3 fraction had a negligeable contribution compared to EC2 and EC1.

In general OC presented the higher contribution (72%) in the carbonaceous (Figure 3.22). Suggesting a high volatile compounds contribution.

OC is emitted form primary and secondary sources. Biomass burning and motor vehicles that release high organic carbon including volatile organic compounds [173]. Secondary

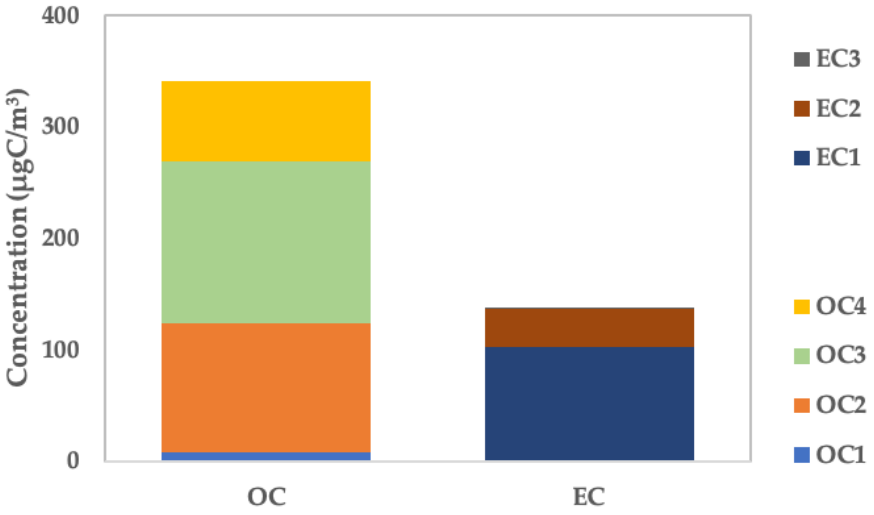


Figure 3.21: Different carbon fractions OC1, OC2, OC3, OC4 and EC1, EC2, EC3 in different samples.

aerosols formation in the atmosphere is also a source of OC.

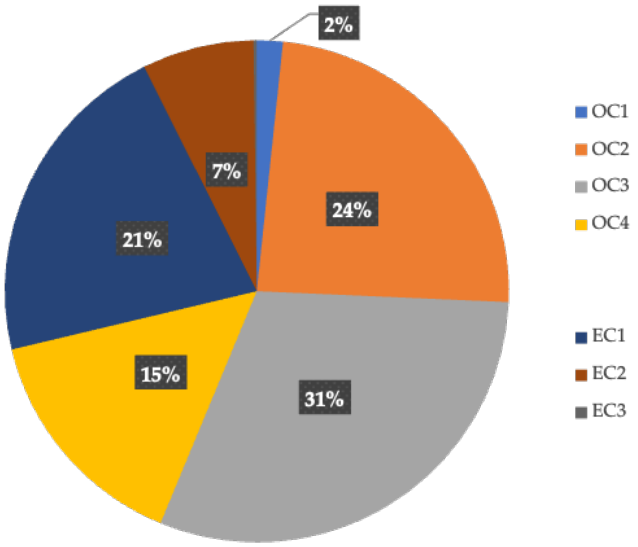


Figure 3.22: Contribution of different carbonaceous fraction; OC1, OC2, OC3, OC4 and EC1, EC2, EC3 in different samples.

EC is exclusively emitted from primary sources and is a good tracer of fossil fuel combustion and motor vehicle emissions. OC/EC ratio in this study was 5 (Figure 3.23). This value was higher than the values reported in Birmingham, UK (0.99 to 2.79), in Japan, Tokyo (1 to 2), in Spain, Barcelona (0.28), in China, Hong Kong (0.8 to 1.6) and (2.99) in Xi'an, in Benin,

Cotonu (4) and [174] [175] [176] [177] [178]. The higher OC/EC ratio in this study compared to others studies suggest a higher contribution from sources other than vehicles emission. Indeed, activities such as cooking and animal husbandry were common.

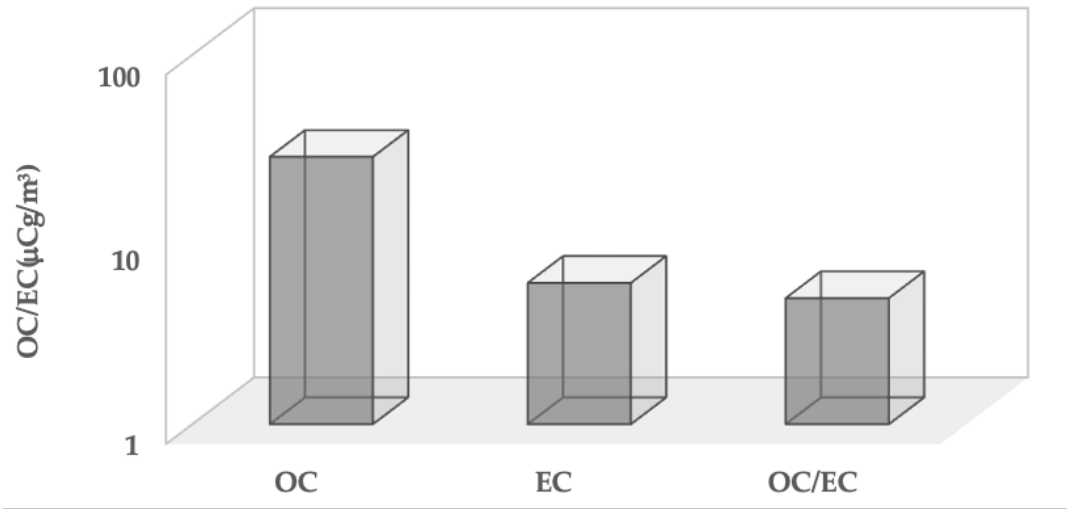


Figure 3.23: Concentration of OC, EC and OC/EC

Moreover, char EC, shoot EC and char EC/soot EC ratio were determined. Char-EC which is characterized by incomplete combustion was obtained by subtracting OP (pyrolyzed fraction) value from EC1 value. Shoot EC; characterized by high temperature combustion was calculated as the sum of EC2 and EC3. Char EC/Soot EC is a good indicator of biomass burning and incomplete combustion [138] [139] [140]. In this study the ratio char EC/soot EC was 1.3. This suggests incomplete combustion sources.

PM metals composition

In this study, the concentration of 35 metals were determined. Figure 3.24 and Table A.3 presents the average concentrations (ng/m^3).

The most dominant metals were Fe, Al, K, Mg, Ca and Na. In, TI, Bi, Ag, and Be showed the lowest concentrations. The metals presenting the highest concentration were soil dust resuspension, traffic indicators and biomass combustion tracers. Fe, Al and Ca were detected from traffic and construction activities. K, Na, Mg from biomass combustion sources. Other

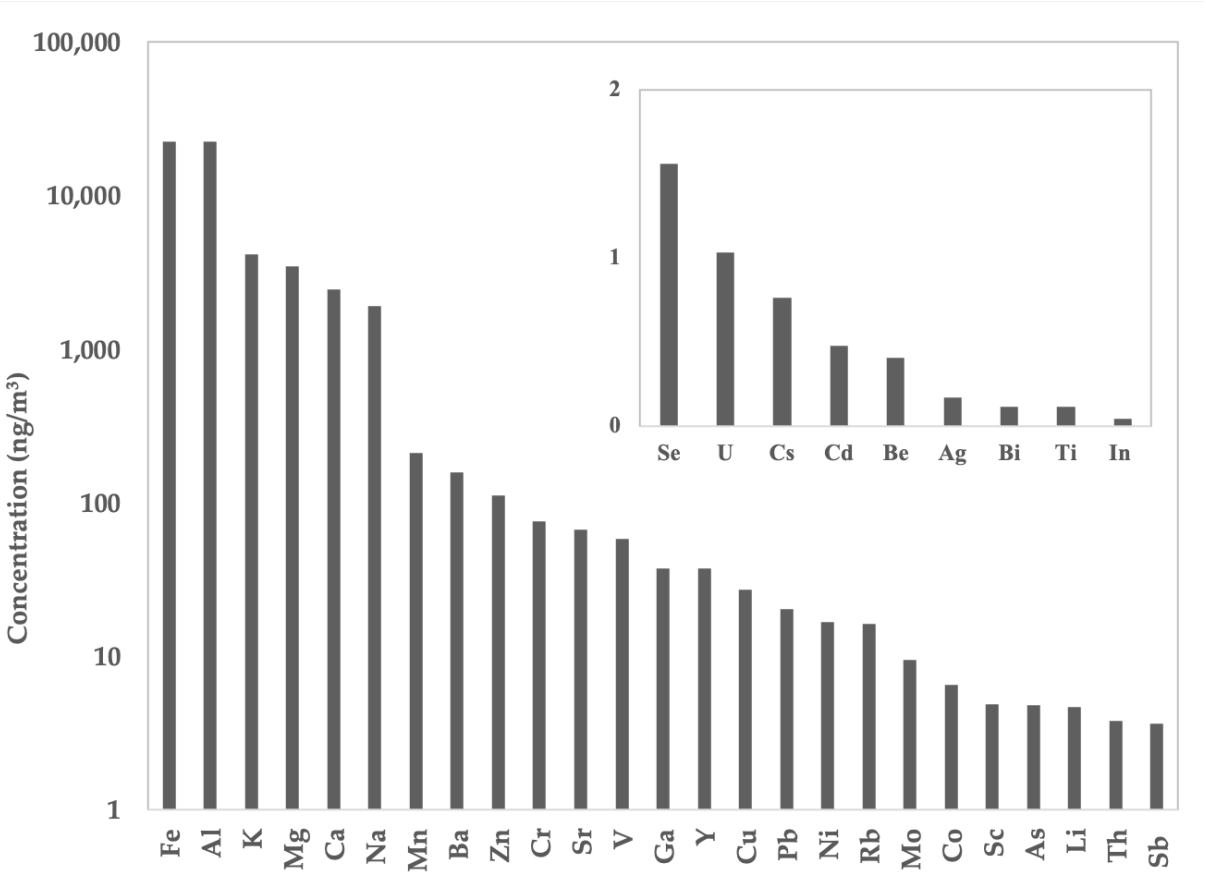


Figure 3.24: Average concentration of the metals

metals (Mn, Ba, Zn, Cr, Sr, V, Ga, Y, Cu, Pb, Ni, Rb, Mo) had significant contribution in the metal composition.

Elements such as Mn, Zn, Ba, Cr, Sr, Cu, Pb, Ni are emitted from anthropogenic activities such as traffic and industries [179] [59] [180] [177]. As there was no industrial unit close to the sampling site, the observed metals were suspected to be emitted from road traffic.

- **Enrichment factors (EFs) of road side PM**

Figure 3.25 and Table 3.12 illustrates the average and standard deviations of EFs of the metals at a typical traffic site in Bamako city. An EF > 1 indicates no influence of anthropogenic activities and, an EF < 1 shows that the measured concentration is higher than the background concentration. There are different levels of enrichment. EF > 3 indicates a minor enrichment, from 3 to 10; moderate enrichment, from 10 to 25; severe enrichment, and > 25; extremely

severe enrichment [181] [182].

The highest EF; indicating extremely severe enrichment were obtained for Se, Sb and Mo Figure 3.25 and Table 3.12. This could be attributable to traffic (emissions from motor vehicles, brake wear, tire, traffic dust), fossil fuel combustion and biomass combustion [183] [184] [181] [185] [186] [187] [188].

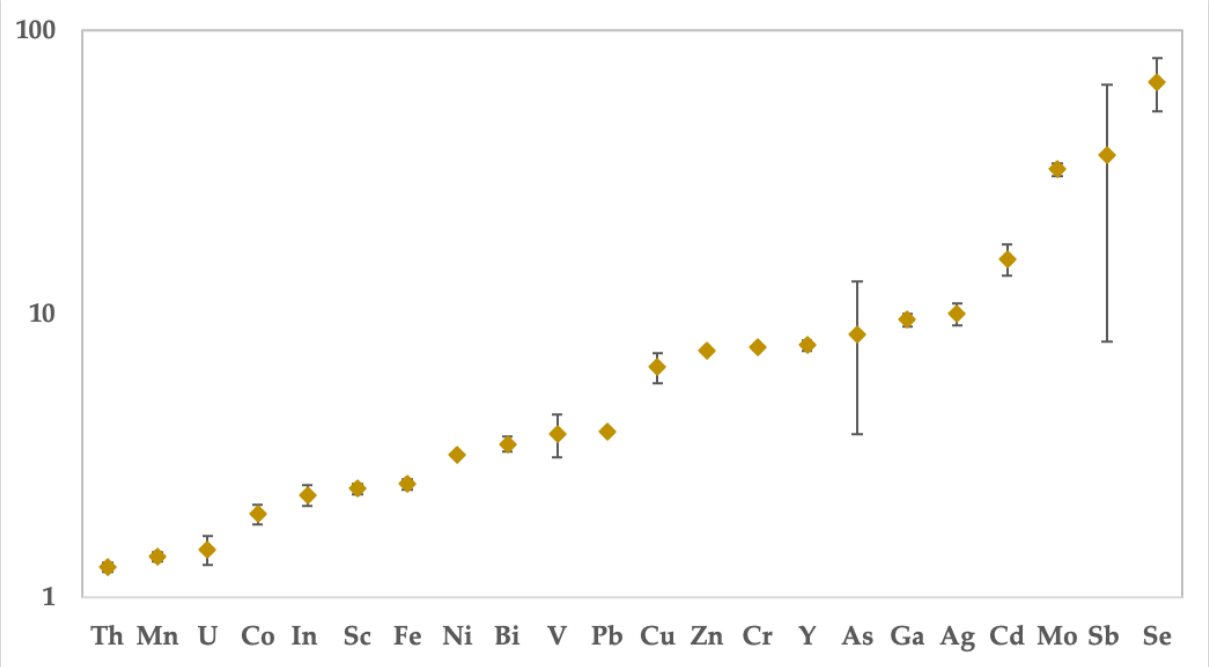


Figure 3.25: Average and standard deviations of enrichment factors (EF) of metals

Elements such as Cd, Cr, As, Zn, Pb known for their harmful effects on health presented moderate to severe enrichment factors. These elements have previously been identified at traffic sites, during combustion processes [179] [181] [185] [180] [177] [188]. Most of the elements had higher concentration than their background level. Demonstrating an influence of anthropogenic activities on the metal's concentration in Bamako.

Table 3.12: Enrichment factors of roadside samples; averages and standard deviations. Values in bold have EF > 1

Elements	EF	Elements	EF
Li	0.75±0.07	**Se**	65.46±2.24
Be	0.52±0.20	**Rb**	0.52±0.02
Na	0.26±0.02	**Sr**	0.73±0.01
Mg	0.90±0.06	**Y**	7.74±4.65
K	0.51±0.02	**Mo**	32.30±28.23
Ca	0.28±0.01	**Ag**	10.00±1.93
Sc	2.41±0.10	**Cd**	15.57±1.74
V	3.78±0.03	**In**	2.38±0.15
Cr	7.59±0.34	**Sb**	36.22±13.85
Mn	1.39±0.05	**Cs**	0.46±0.02
Fe	2.52±0.01	**Ba**	0.84±0.09
Co	1.97±0.15	**Ti**	*
Ni	3.18±0.21	**Pb**	3.83±0.79
Cu	6.51±0.02	**Bi**	3.48±0.64
Zn	7.41±0.09	**Th**	1.28±0.04
Ga	9.52±0.86	**U**	1.48±0.17
As	8.42±0.48		

3.3.2 Source of roadside PM

To evaluate the contribution of different emission sources to the PM, CMB and PCA were using.

The source distribution by CMB model revealed that the PM at the sampling site was largely influenced by dust resuspension. This accounted for 70% in total including 63% attributed to soil and road dust and 7% to brake dust. Biomass burning had a significant contribution to the PM pollution (16%) and vehicular emissions presented 5%. Other sources accounted for a total of 9% (Figure 3.26). The sources might include street food preparation, animal husbandry and traditional forge. These activities were common at the sampling site and might contribute to other sources.

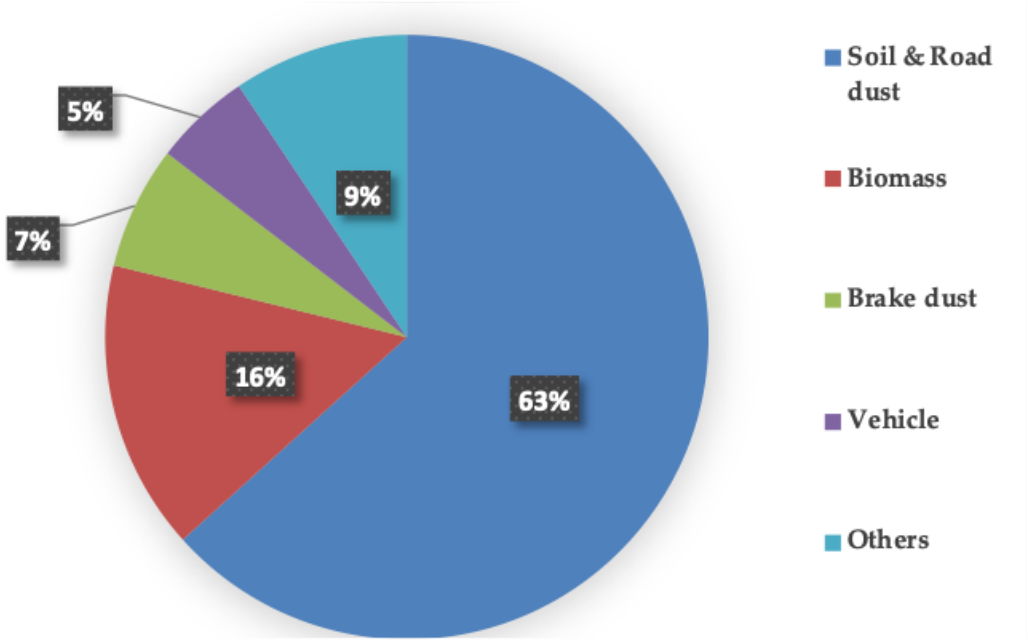


Figure 3.26: Source contribution to PM by CMB model

Table 3.13, presenting the estimation of source contribution by PCA. Where Eigenvalues indicate the most important principal component. The higher the value is, the more important the PC. The variability percentage expresses the contribution of each principal component and the cumulative percentage represents the progressive accumulation of the variability percentage up to 100%. The loading factors indicate the more representative air pollutant in each PC. A

Table 3.13: Source contribution to PM by PCA; Principal components

	PC1	**PC2**
Eigenvalue	2.231	0.707
Variability (%)	74.362	23.582
Cumulative %	74.362	97.943
Cl	**0.583**	0.417
N O_3	0.023	0.973
SO4	0.122	**0.874**
Na	0.263	**0.726**
NH4	0.498	**0.502**
K	**0.997**	0.003
Ca	0.047	**0.943**
OC	**0.920**	0.061
EC	**0.602**	0.375
Al	0.047	**0.943**
Sc	**0.997**	0.003
V	**0.997**	0.003
Cr	**0.996**	0.004
Fe	**0.912**	0.033
Mn	**0.501**	0.499
Zn	**0.996**	0.004
As	**0.997**	0.003
Se	**0.997**	0.003
Sb	**0.997**	0.003

factor of more than 0.5 is considered as strong, range of 0.4 – 0.49 is considered as moderate and less than 0.3 is considered as weak [189].

PCA revealed 2 principal components (PCs) that explained 97,9% of the total variance. PC1 explainned 74.36% of the variance and was highly loaded with Sc, V, Cr, Fe, Zn, As, Se, Sb, Al but also K, OC and EC. Metals are generally naturally abundant elements but, concentrations higher than their background concentrations can be observed due to the enrichment from diverse source. Fe, Mn, V, are highly abundant in the earth crust thus, mostly originate from soil dust. Sb, As, Cr, Zn, Sb have been associated with traffic emissions from diesel vehicles, brake and tire wears, coal combustion [190][179] [191] [192] [193] [194] [177] [188]. In this study, the EF estimation indicated that anthropogenic activities contribute to the observed concentrations

of the highly loaded metals in PC1 (Table 3.13 and Table 3.12). K, OC and EC are well known biomass and biofuel combustion tracers. PC1 suggests that anthropogenic activities have a great impact on the air quality at the sampling site.

PC2 explained 23.58% of the variance and was highly loaded with Al, Ca, Na and Sulfate, Nitrate and Ammonium (SNA). The fact that PCA regrouped these metals with SNA indicated that they might be generated from similar sources. SNA are secondary aerosols and their presence could be explained by traffic emissions including gasoline and diesel fuel from vehicles exhausts and tire and brake wear. They can be produced from precursors such as SO_2, NOx, NH_3 emitted from traffic and other anthropogenic activities [148] [195] [196]. Al, Ca and Na might have originated from the resuspension of the soil dust on roadsides. In contrary to the highly loaded metals in PC1, EF did not indicate the enrichment of Al, Ca and Na by anthropogenic activities. PC2 suggests a mix contribution linked to natural source and anthropogenic activities.

PCA results are in line with CMB results. Both indicated that the dust resuspension from anthropogenic activities was the most the dominant contributor to PM. Traffic emissions (diesel and gasoline fuel combustion, tire and brake), and biomass burning presented lower but significant contribution to the PM pollution. In Bamako, streets especially walk side are unpaved and are not in good condition (Figure A.5c). These local conditions might have resulted to the high observed dust contribution. From the findings it appears that an underdeveloped infrastructure can greatly impact urban air quality.

3.3.3 Health exposure assessment

Similarly to the households emission exposure risk assessment, the health risk from the exposure to particulate matter from the traffic sector have been estimated through the inhalation route. HQ for a single heavy metal and HI for multiple heavy metals were evaluated.The calculations for public transportation drivers were done separately due to the difference in the exposure time. They spend a considerable amount of time in traffic compared to other inhab-

itants. Table 3.14 presents the health risk assessment results from the exposure to PM from a typical roadside.

- **Non-carcinogenic risks**

Table 3.14a presents the HQ and HI in adults children and public transportation drivers. The HQ for Mn exceeded the recommend exposure limit in public transportation drivers. HI in adults was within the safe exposure limit. But the exceed 1 in children (1.35). The hazard index in public transportation drivers was almost 3 times as much as the safe exposure limit.

Table 3.14: Health risks assessment of toxic metals in adults and children. Adl: adults, Chl: children, Dri: Drivers.
*: negligible

	Traffic		**Traffic DRI**
	Adl	Chl	Adl
Cr	0.06	0.06	0.33
Mn	0.34	0.34	1.85
Ni	0.09	0.92	0.49
As	0.03	0.03	0.14
Cd	*	*	0.02
Be	0.04	*	0.05
HI	0.55	1.35	2.88

(a) Non-Carcinogenic

	Traffic		**Traffic DRI**
	Adl	Chl	Adl
Cr	2.50E-05	7.29E-05	1.37E-04
Ni	1.10E-07	3.22E-07	6.07E-07
As	5.66E-07	1.65E-06	3.11E-06
Cd	2.36E-08	6.87E-08	1.30E-07
Pb	6.62E-09	1.93E-08	3.64E-08
Be	6.50E-07	1.63E-07	1.24E-06
T-CR	2.63E-05	7.51E-05	1.43E-04

(b) Carcinogenic

- **Carcinogenic risks**

Table 3.14b indicates the carcinogenic risk from the exposure to heavy metals in adults and children. The values were above the lower limit of 10^{-6} but bellow the unacceptable level of 10^{-4} in adults and children. Public transportation drivers presented a value above the unacceptable level in traffic. The older age is one of the factors increasing the risk of cancers occurrence yet, the carcinogenic risk was higher in adults compared to children.

CR values were below the unacceptable level but above the lower safe exposure limit. The risks exposure presented in this research was higher compared to the risk exposure reported in

previous researches in Japan, china and India [159] [161] [197]. Although the metal composition was not dominated by toxic metals, the health risk assessment study indicated possible adverse effects on human health. Furthermore, public transportation drivers had the highest CR due to the higher exposure time in traffic. These suggest that even though the toxic metals concentrations were lower compared to the non-toxic ones, the repeated exposure and the exposure duration pose serious health issues. Therefore, it is important to implement strict measures for the population's health safety improvement in Bamako.

3.3.4 Conclusion

In this study, the composition of PM from a typical roadside in Western Sub-Saharan Africa was determined. Samples were collected on filters in Bamako city. The results indicated that the ion composition was dominated by cations. Ca^{2+} represented 52% of the ions. OC was the dominant carbonaceous and the ratio char EC/soot EC indicated that the sampling site was characterized by incomplete combustion sources. The EF indicated a significant influence of anthropogenic activities to the metals' concentration. The source distribution study showed that dust resuspension and other anthropogenic activities including biomass and biofuel combustion were the main outdoor PM emission sources. The health risk assessment indicated that the exposure to PM was unsafe. HI values exceeded the safety limit of 1 in children and public transportation drivers. CR exceeded the lower limit of exposure of 1E-6 but were below the unacceptable level of 1E-4. Except for public transportation drivers for the traffic microenvironment (CR $\geq$ 1E-4). The cancer risk was higher in adults than children.

The findings indicated that it is crucially important to control the emission sources. Both local government and inhabitants should participate in this effort. There was a high influence of anthropogenic activities on the outdoor PM pollution. Soil dust resuspension and traffic emissions were the main contributors. This was related to the poor infrastructure but also the condition of the aging vehicle fleet. Consequently, to reduce dust resuspension the regular maintenance of streets is highly recommended. Developing a convenient public transportation system, promoting the use of public transportation, cycling and walking and, implementing the

laws and regulations in the traffic sector could considerably reduce outdoor emissions.

This study provided important information on outdoor air pollution in Bamako city. The findings highlighted the need to initiate a regular air pollution monitoring systems for health and environment safety. Furthermore, the results presented scientific data that are essential as preliminary step in promulgating air pollution mitigation strategies and, reducing the population exposure to PM.

Criteria ambient air pollutants

Referring to the earth history, air pollution is not a new phenomenon. Human began to pollute their environment hundreds of thousands of years ago. Archaeologists found evidences that early human began using fire 400, 000 years earlier [198]. It is therefore evident that the interactions between humans and their surroundings always affected the biotic and the abiotic environments.

Since the industrial revolution air pollution began to be felt. This revolution associated to the population growth resulted to a great increase in atmospheric pollution. Indeed, the rapid urbanization, the increase in the number of vehicles, industrial activities lead to the over-exploitation resources (use of chemicals and fuel). Which, dramatically decreased the air quality in many urban cities. Today, the traffic sector and the use of fossil for energy generation are the main pollution sources. Especially, in developing countries where; biomass and bio-fuel are the main energy sources. The fuel quality and parking fleet greatly impact traffic emissions.

Scientists identified particulate matter (PM_{10} and $PM_{2.5}$), ozone (O_3), nitrogen oxides (NOx), carbon monoxide (CO), sulfur dioxide (SO_2) as common majors air pollutants in urban cities. These criteria air pollutants from anthropogenic activities are the main concerns of public heaths and environmental issues. The emission these pollutants is continuously causing various problems. Different factors can affect these. The weather condition is one of the factors that can have a great impact on the emitted air pollutants and hence, the air quality.

In this section, the variation of the concentration of five major air pollutants (O_3, NO_2, CO,

SO_2, PM) along with their relationship with meteorological parameters (temperature, humidity and wind speed) were investigated. The samplings were performed at a typical road side in Bamako city during the dry and wet season. The results are presented below.

3.4 Major air pollutants

3.4.1 Variation in the major pollutants concentrations

Descriptive statistics of the major air pollutants concentration

Table 3.15 summarizes the results of the descriptive statistic of the major air pollutants (NO_2, O_3, SO_2, CO, $PM_{2.5}$, PM_{10}) and the meteorological parameters (temperature, humidity, wind speed) for six months sampling period (from mid-February to mid-August). This includes, the mean, the maximum, the minimum, the 25^{th} (1^{st} quartile) the median and 75^{th} (3^{rd} quartile). The results revealed high concentrations for all the pollutants. CO and SO_2 showed the highest mean values (3.0E+03 ± 2.E+02 and 1.1E+03 ± 3.E+01 $\mu g/m^3$), followed by PM_{10} , O_3, NO_2 and $PM_{2.5}$ respectively.

Table 3.15: Descriptive statistics of air pollutants and meteorological parameters

	Mean	Maximum	Minimum	Q1	Median	Q3
Air pollutants						
NO_2	3.0E+02 ± 8.E+00	5.3E+02	5.5E+01	2.1E+02	3.0E+02	4.1E+02
O_3	6.5E+02 ± 1.E+01	1.1E+03	1.9E+02	4.8E+02	6.6E+02	8.1E+02
SO_2	1.1E+03 ± 3.E+01	2.4E+03	4.3E+02	7.6E+02	1.0E+03	1.2E+03
CO	3.0E+03 ± 2.E+02	1.0E+04	4.6E+02	1.4E+03	2.2E+03	3.7E+03
$PM_{2.5}$	1.0E+02 ± 6.E+00	5.1E+02	1.0E+00	2.5E+01	7.9E+01	1.6E+02
PM_{10}	6.8E+02 ± 4.E+01	1.9E+03	4.1E+01	2.5E+02	5.7E+02	1.0E+03
Meteorological parameters						
Temperature	3.7E+01 ± 2.81E-01	4.3E+01	2.7E+01	3.4E+01	3.7E+01	4.0E+01
Humidity	6.5E+01 ± 1.92E+00	1.0E+02	1.5E+01	3.7E+01	6.6E+01	6.5E+01
Wind speed	3.4E+00 ± 9.70E-02	9.8E+00	1.8E+00	2.6E+00	3.0E+00	3.4E+00

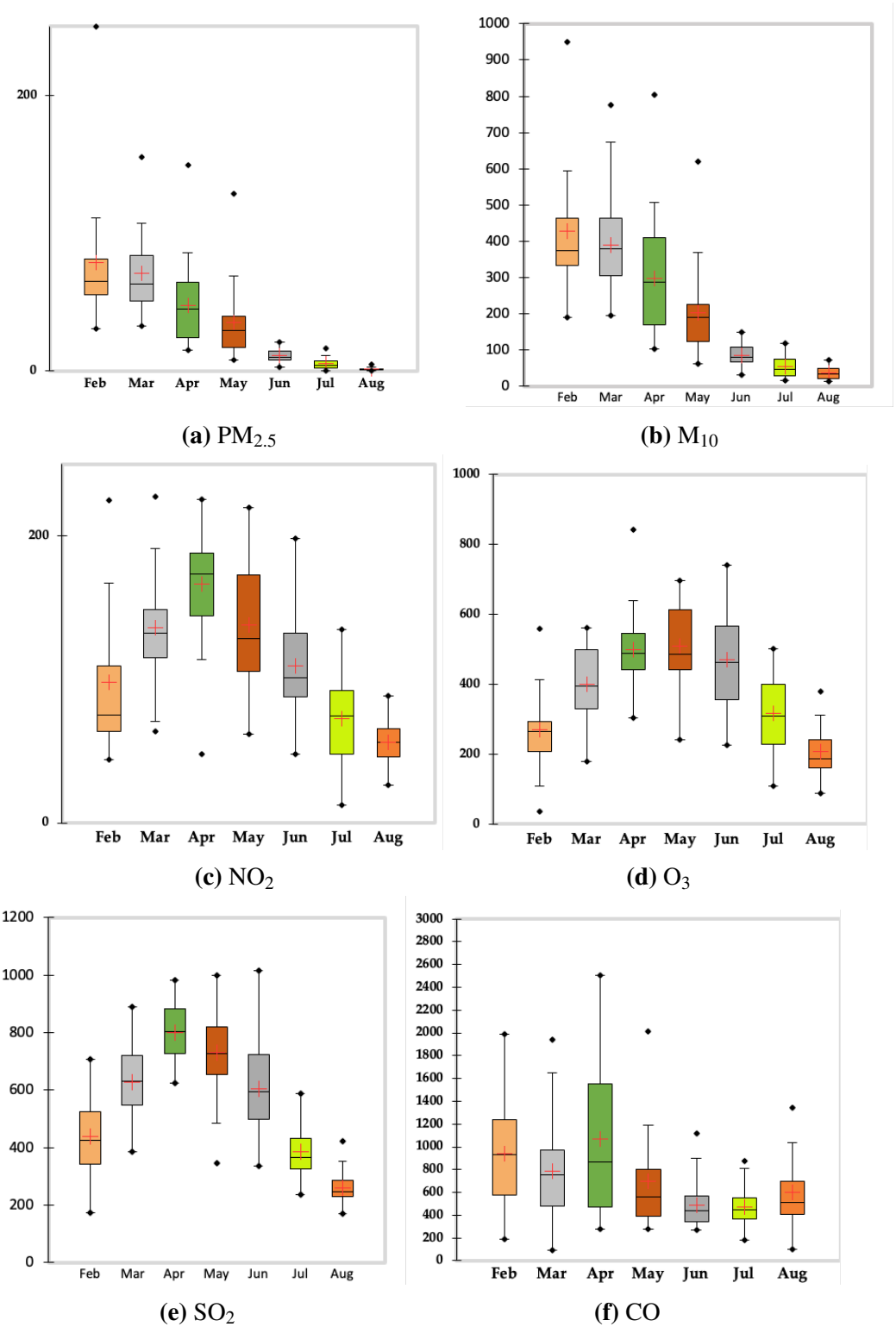
Monthly concentration and seasonal variation and of the criteria air pollutants

From the results, there is clear difference in the pollutants concentration between the rainy (wet) and dry season. The concentration of all the pollutants were substantially higher in the

dry season (corresponding to the month of February to May) compared to the wet season (corresponding to the month of Jun to August). Especially, the concentration of $PM_{2.5}$ and PM_{10} showed a great increase of 98% and 92% respectively and this, from the wet season to the dry season. Similarly, NO_2, SO_2, CO and O_3 showed an increase of 60%, 58%, 57% and 55% respectively. The highest monthly average values were recorded in April for CO, SO_2 and NO_2 with values of 1065.82 $\mu g/m^3$, 798. $\mu g/m^3$, 166.58 $\mu g/m^3$. For O_3, the highest was recorded in May (508.761 $\mu g/m^3$), and for PM_{10} and $PM_{2.5}$ in February (426.42 $\mu g/m^3$ and 78.62 $\mu g/m^3$). The minimum temperature was recorded during August and the maximum temperature during April. Humidity showed an increasing trend from February to August.

Figure 3.27 illustrates the box plots of the criteria air pollutants from February to August 2021. The box plots contain five different information about the pollutants and meteorological parameters. This information is represented in four different fractions that contain each 25% of the data set information. A larger size of the box indicates a higher variability in the pollutant concentration or a larger variability in the meteorological parameter level. The upper and lower whisker from the first quartile (Q1) to the third quartile (Q3) indicate the maximum and minimum value. The red cross shows the mean value. The vertical line dividing the box plots represents the middle value of the data set; median. The distance from the lower whiker to upper whisker shows how spread out the data set is. Black dots are outliers; representing abnormal values.

A wide distribution over the sampling period was observed for all the pollutants. PM levels decreased considerably in the rainy season. The level of CO, SO_2, O_3 and NO decreased in the rainy season. However, low concentrations (of CO, SO_2, O_3 and NO) were also observed in the beginning of the dry. In general, the highest concentrations were observed in April and May corresponding to the hottest months. Except for the PM particulate matters showing the highest concentration in February.

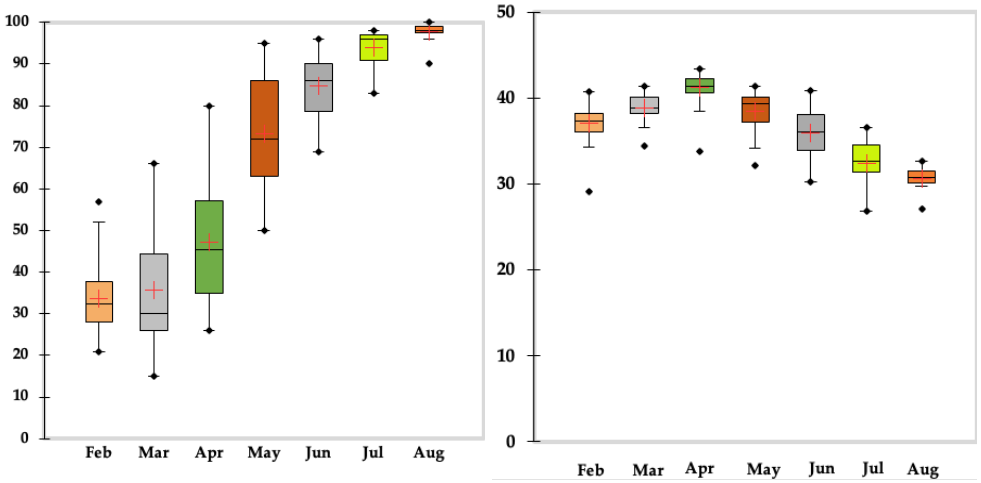


(a) $PM_{2.5}$ **(b)** M_{10}

(c) NO_2 **(d)** O_3

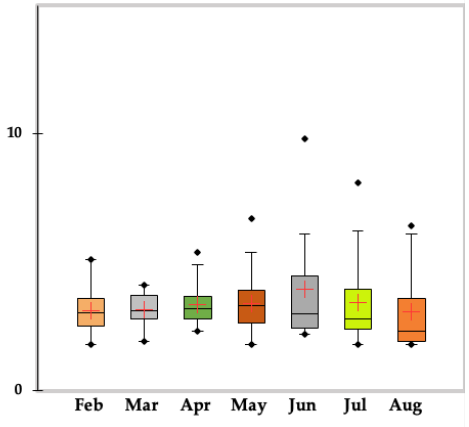
(e) SO_2 **(f)** CO

Figure 3.27: Monthly box and whisker plot of the major air pollutants (NO_2, O_3, SO_2, CO, $PM_{2.5}$, PM_{10})in $\mu g/m^3$. Feb: February, Mar: March, Apr: April, Jun: June, Jul: July, Aug: August



(a) Humidity (%)

(b) Temperature (°C)



(c) Wind Speed (m/s)

Figure 3.28: Meteorological parameters (Temperature, humidity and wind speed)

The concentration of PM_{10} and $PM_{2.5}$ decreased from 320.94 to 61.41 $\mu g/m^3$ and 57.04 to 6.6 $\mu g/m^3$ respectively from the dry to wet the season. In the dry season $PM_{2.5}$ contributed to 18% of PM_{10} and 11% in the wet season. The contribution of $PM_{2.5}$ to PM_{10} does not significantly change between both seasons. PM_{10} concentration is 6 times higher than $PM_{2.5}$ concentration in the dry season but 9 times higher in the wet season. Suggesting that in the dry season $PM_{2.5}$ could be generated from multiple sources. Mainly the primary emissions sources such as the emissions from motor vehicles and combustion sources. Secondary formation through atmospheric processes such as the condensation and the photochemical reaction of NO_2 and SO_2. And, dust resuspension from traffic and other anthropogenic activities. But, in the wet season with less favorable conditions for primary pollutants reaction and the lower dust resuspension, $PM_{2.5}$ might be mainly generated from primary emission sources. Whereas, PM_{10} is most likely originated from dust resuspension in both seasons.

O_3, SO_2, NO_2 and CO show a seasonal variation with the highest concentration in April and May, lower concentrations were observed in February and March. The lowest concentrations occur in Jun and July. The high concentration in the month of April and May was more likely due to the meteorological conditions. The possible reason for the higher levels in this period could be due to an association of factors including the higher temperature and lower humidity, the photochemical reaction, the poor dispersion. The higher temperature might be favorable for secondary pollutants formation like O_3 through oxidation processes. The dry season in Bamako is from October to May. But April and May are the hottest moths with temperature reaching 43°C. Which might accelerate the production of pollutants such as O_3, NO_2 , by photochemical reactions as the sunlight is the strongest.

The mean concentration for CO was the highest; 2974.59 $\mu g/m^3$ during the sampling period (Table 3.15). This might be related to the incomplete combustion of fuel from the traffic. $PM_{2.5}$ and PM_{10} have a similar trend and show a decreasing concentration from February to August. In fact, particulate matters concentration reaches the highest in the dry season corresponding to the months where Harmattan hits the most (January to May). Harmattan blows from the North-Est;

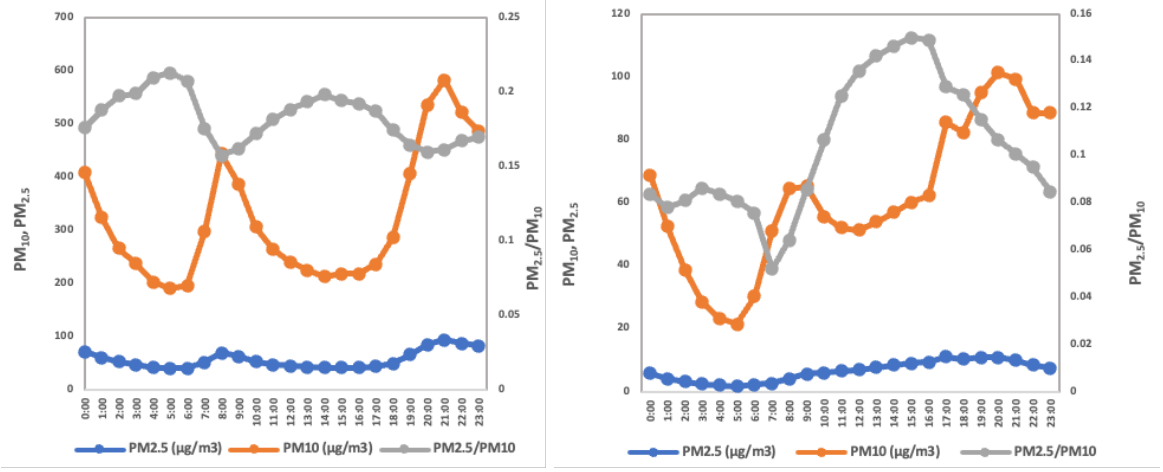
Sahara Desert to the West, therefore carries particulate matters. Indeed, there is a domination of wind blowing from the North-East during the dry season. In the wet season the wind mostly originated from the north with a small contribution from the West (Figure A.6a). As Harmattan is characterized by the wind blowing from North-Est, it might contribute to higher level of PM in the dry season.

July and august corresponding to the rainy season presented the lowest concentrations for all the criteria pollutants. The lowest concentration might be influenced by the local conditions including high relative humidity and lower temperature compared to the other months. The highest relative humidity and the lower temperature were recorded during the rainy season (Figure 3.28). These conditions were less favorable for the secondary pollutants' formation and more favorable for the wet deposition process and the acid rain formation from NO_2 and SO_2. Plus, the rain is the most abundant between Jun and August. PM resuspension would hence be significantly lower. Although the wind speed was generally not high during the sampling period, the highest wind speeds were recorded from Jun, corresponding to the period where the decrease in the concentration was observed.

The ratio of $PM_{2.5}$ to PM_{10}

The faction of $PM_{2.5}$ in PM_{10} varies according to different location and time [199]. Low $PM_{2.5}$ over PM_{10} ratio indicates a significant contribution of PM_{10}. The traffic can contribute to higher $PM_{2.5}$ by pollutants from the vehicles 'engines and the dust resuspension. At night the concentration of $PM_{2.5}$ does not decrease significantly with the cessation of the traffic and other anthropogenic activities as the lower inversion layer brings the accumulated fine particles closer the ground.

In this study, there is a seasonal variation of the $PM_{2.5}/PM_{10}$ ration with higher ratio during the dry season (Figure 3.29). The ratio shows a different daily variation trend in the two seasons. And, has a large fluctuation in wet season compare to dry season. The wet season was characterized by a clear increase in the ratio from morning to afternoon with the highest peak



(a) Dry season **(b)** Wet Season

Figure 3.29: Daily variation of $PM_{2.5}/PM_{10}$ ratio from February 2021 to august 2021

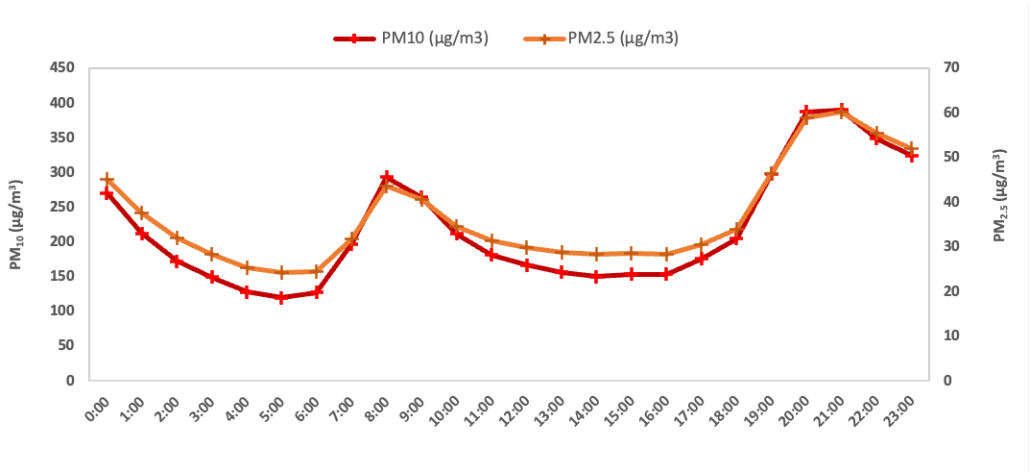
occurring at 3 p.m. While the dry season did not show a clear daily variation. Slightly higher $PM_{2.5}$ /PM_{10} ratio was observed at night with a peak occurs at 5 a.m.

A higher ration in the wet season during daytime indicates a higher $PM_{2.5}$ contribution to PM_{10} concentration during the daytime compared to the night time. This daily variation could be explained by the influence of traffic. In the wet season, there is less dust resuspension leading to a decrease in PM especially, PM_{10} concentration. $PM_{2.5}$ is suspected to originate from other sources (vehicles engines) in addition to dust resuspension. Considering that, with dust suspension being lower in the wet $PM_{2.5}/PM_{10}$ would be higher during day time in the wet season. The dry season on the other hand is characterized by dust resuspension. There is no clear decrease in the ratio from day to night compared to the wet season. This low variation in the daily trend of the ration could be attributed to the contribution of traffic and other anthropogenic activities during day the time. This might be due to the temperature inversion; stronger during the dry season in Bamako [200]. This causes the deposition of coarse PM and the accumulation of fine PM during night time and hence, would be favorable for a higher ratio [199]. Lower inversions occurring at night brings the accumulated PM at lower altitudes.

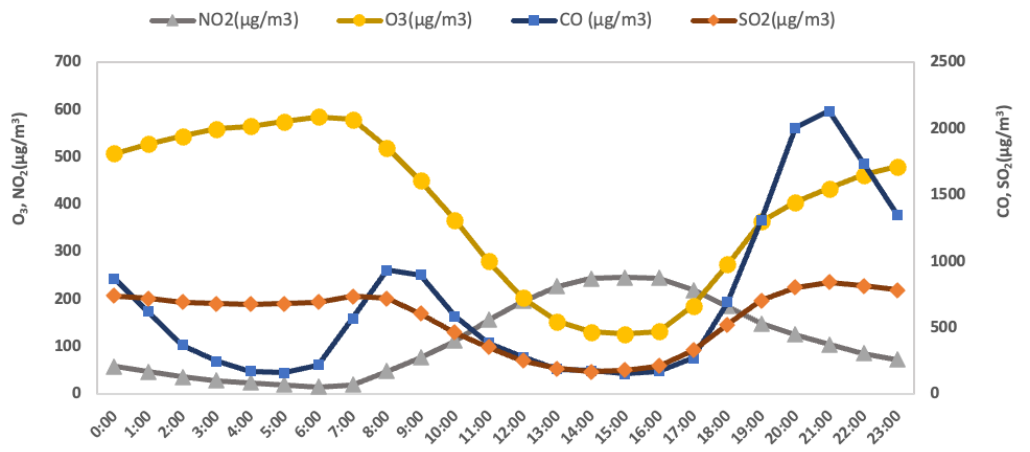
Daily profile of the major air pollutants

In order to better reveal the behavior of the air pollutants and determine their relationship

with each other, we investigated their daily profiles. Figure 3.30 illustrates the daily variation of ambient of air pollutants from February to August 2021. Figure 3.30a for PM_{10} and $PM_{2.5}$ concentration and Figure 3.30b for NO_2, O_3, CO and SO_2.



(a) PM_{10} and $PM_{2.5}$



(b) NO_2, O_3, SO_2, CO

Figure 3.30: Daily profile of major pollutants from February 2021 to august 2021.

No significant changes in the daily patterns of the pollutants were observed although they showed a clear decrease in concentration from the dry to the wet season (Figure A.8).

In addition of having similar monthly and daily pattern, $PM_{2.5}$ and PM_{10} also had an identical hourly variation. The hourly variation of ambient $PM_{2.5}$ and PM_{10}, showed two peaks; one in the morning and another one in the evening. The mean concentration for $PM_{2.5}$ and PM_{10} starts to increase around 6 a.m and reaches a peak of 43.65 and respectively 293.56 $\mu g/m^3$ at 8 a.m. Whereafter, a continuous decrease was observed. For evening hours, the mean concentration

starts increasing from 5 p.m and reaches a peak of 60.37 and 390.84 $\mu g/m^3$ at 9 p.m respectively.

Similarly to PM, CO is characterized by two peaks that occurred in the morning and in the afternoon corresponding to the traffic rush hours. Visible higher peaks were observed in the evening compared to the morning. Although the traffic decreased after the rush hours, notable concentrations were observed in between the highest daily peaks. Indicating the contribution of other anthropogenic activities such as biomass combustion (charcoal and wood), small businesses and street food preparation. These activities are common along the road side in Bamako city. As a matter of fact, there is a restaurant located at 50 meters from the sampling site using coal for cooking. These activities could also explain SO_2 daily profile. The daily pattern seems to correlated with local activities (including the morning and evening peaks). SO_2 from urban areas is usually associated with fossil fuel combustion and the use of diesel and gasoline containing sulfur. The daily peaks correspond to the rush hours. Fuel with very high sulfur content is used in Mali (threshold of 10,000 ppm). This might highly contribute to the observed SO_2 concentration. The morning peaks were probably associated with the increase in traffic for the commute and other anthropogenic actives. The significantly higher concentration in the evening could be associated to the inversion layer effect in addition to the traffic.

At last, the variation of PM, CO and SO_2 concentrations through the day were visibly related to emissions from cars and motorbikes engines, dust resuspension from traffic and other anthropogenic activities.

O_3 and NO_2 show a very particular daily variation compared to the typical daily trends. The highest concentrations for O_3 were observed at night. As the sun goes down, the concentration starts to increase in the evening around 7 p.m, reaches the highest at 6 a.m and start decreasing from 7 a.m as the sun rises. The lowest concentration was recorded between 12 p.m to 5 p.m. NO_2 showed an inverse trend with low concentration at night and high concentration during day time. The concentration increases from 8 a.m reaches a peak at 3 p.m and decreases as the sun goes down and anthropogenic the activities decrease. The lowest concentrations were

observed from 2 a.m to 7 p.m. These trends were consistent through the whole sampling period (Figure A.7). The very particular trend of O_3 could have several explanations. O_3 is a secondary pollutant and cannot be generated at night nevertheless, the highest concentration was observed at night. Suggesting that a considerable fraction of the generated O_3 during day time through reaction (1.1) might be trapped and accumulate under an inversion layer. In Bamako, thermal inversion is observed for the major part of the year but, it is the strongest during the dry season [200]. The inversion layer goes down with the sunset bringing the isolated pollutants near the ground. This phenomenon and the decrease of local activities results to an increase of O_3. The low wind speed (Figure A.6) was not favorable for pollutants dispersion. Moreover, a low wind speed is not favorable for the dispersion process through pollutants transport. As the sun rises and traffic increases NO_2 will be produced from the oxidation of NO by O_3 through reaction (3.1). This reaction results to the destruction of a portion of the photochemically produced O_3. Therefore, a decrease in O_3 concentration and an increase in NO_2 concentration. This could further explain the daily pattern of these pollutants. O_3 and NO_2 showed a similar behavior in Israel; Jerusalem and Tel-Aviv [201].

$$NO + O_3 \rightarrow NO_2 \tag{3.1}$$

The high night time concentration of the major pollutants in this study is most likely due to the thermal inversion effect.

3.4.2 Relationship between major pollutants and between meteorological parameter and major pollutants

Table 3.16 presents the correlation between the primary pollutants and meteorological parameters from February to August 2021. Temperature was positively correlated to all pollutants. It showed a strong positive correlation especially with NO_2. This might be due to the increase in NO_2 formation from the increase of radiation (reaction 3.1). Similarly, O_3 and SO_2 had positive correlation with temperature but, less significant compared to NO_2. PM ad CO showed lower correlations

Table 3.16: Correlation between Air pollutants and Meteorological parameters

Correlation matrix (Pearson)

Variables	NO_2	O_3	SO_2	CO	$PM_{2.5}$	PM_{10}	Temp	Hum	Wind speed
NO_2	1	0.548	0.522	0.205	0.303	0.365	0.855	-0.453	0.136
O_3		1	0.481	-0.043	0.068	0.083	0.560	-0.153	0.250
SO_2			11	0.687	0.465	0.579	0.518	-0.374	0.110
CO				1	0.634	0.688	0.174	-0.391	-0.003
$PM_{2.5}$					1	0.917	0.399	-0.727	0.235
PM_{10}						1	0.421	-0.711	0.184
Temp							1	-0.659	0.307
Hum								1	-0.4961
Wind speed									1

Unlike temperature, humidity had a negative effect on the pollutants' concentration. Especially on particulate matter; showing a strong tendency to decrease with the increase of the relative humidity. Indicting that humidity might have been alleviating PM concentration during the sampling period. NO_2 and SO_2 are soluble and can dissolved in water which can explain their negative correlation with humidity. They can contribute to acid rain formation under high humidity.

Except particulate matter and O_3, wind speed showed no significant correlation with air pollutants. Although wind speed usually plays an important role in ambient air pollutants concentration variation, in Bamako the measured level of NO_2, SO_2, CO showed no strong correlation with wind speed. The observed level of these pollutants might be due to local emission rather than pollutants transport. Figure A.6 show very low wind speeds over the sampling period.

Principal component analysis (PCA)

Principal component analysis was used to determine the dependence of meteorological parameters on the concentration of the criteria air pollutants. And, to identify the air pollutants that have the greatest impact on the air quality.

The PCA presented nine principals in total (Table 3.17 and Figure A.9). Over 94% of the

cumulative variance was explain by the five first principal components.

Table 3.17: Principle components and factor loadings. Temp: Temperature ; Hum: Humidity

	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**
Eigenvalue	4.434	1.797	1.190	0.704	0.397	0.194	0.139	0.086	0.058
Variability (%)	49.270	19.962	13.226	7.824	4.407	2.157	1.549	0.959	0.645
Cumulative%	49.270	69.232	82.458	90.282	94.690	96.847	98.396	99.355	100.000
Factor loadings									
NO_2	0.700	0.514	-0.204	-0.316	-0.169	0.247	0.017	-0.101	-0.058
O_3	0.437	0.717	-0.199	0.320	0.365	-0.038	0.133	-0.036	0.020
SO_2	0.764	0.019	-0.465	0.349	-0.124	-0.115	-0.211	0.001	-0.071
CO	0.638	-0.191	-0.341	0.220	-0.239	0.027	0.230	0.016	0.045
$PM_{2.5}$	0.805	-0.449	0.145	-0.087	0.281	0.104	0.024	0.129	-0.123
PM_{10}	0.840	-0.440	0.027	-0.071	0.201	0.088	-0.132	-0.087	0.146
Temp	0.779	0.501	0.030	-0.274	-0.118	-0.101	-0.013	0.184	0.089
Hum	-0.815	0.087	-0.445	0.186	0.045	0.265	-0.069	0.127	0.049
Wind speed	0.371	0.222	0.745	0.458	-0.166	0.137	-0.027	0.017	0.011

PC1 explains 49,27% of the total variance and showed high factor loading for all pollutants except O_3. Indicating that particulate matters ($PM_{2.5}$ and PM_{10}), SO_2, NO_2, CO were the major air pollutants affecting the air quality at the sampling site. PM, SO_2 and NO_2 had the strongest factor loadings. This suggests that human activities such as biomass combustion, traffic, dust resuspension were sources of local air pollution during the sampling period. The site is located closed a typical road side but, it is influenced by many other anthropogenic activities as such as food preparation and small shops as aforementioned. PC2 contributed to 19.962% of the variance and was highly loaded for O_3 and NO_2. Indicating that O_3 also had a major contribution to the air pollution. PC2 suggested a mix of primary pollutants and secondary pollutants emission. O_3 is a secondary pollutant that might be produced from photochemical oxidation of its precursors in presence of sunlight (reaction 1.1). NO_2 and CO might have been the main O_3 precursors. PC2 indicates contribution from traffic and photochemical reactions. Indeed, PC1 and PC2 showed high factors for temperature. Strong radiation is favorable for O_3 formation. The negative loading factor of humidity might indicate a favorable condition for high pollutants concentration with a decrease in humidity. Table 3.17 and Figure A.10 confirm the negative correlation between humidity and air pollutants. PC3 contributed to 13,22% and was loaded

for wind speed. Wind speed has a slight contribution to air pollution, especially for PM (Table 3.17). There was no significant contribution for the other PCs.

The PCA suggests a strong anthropogenic influence on the air quality as, local emission represent the main contribution sources.

3.4.3 Conclusion

This section presented the air quality level based on major air pollutants concentrations recorded over a six months period in Bamako city (February to August 2021). The relationship between meteorological parameters and the major atmospheric pollutants (O_3 , NO_2, CO, SO_2, PM) was assessed by using hourly, daily and monthly average values.

CO presented the highest mean concentration of 2975 $\mu g/m^3$ over the sampling period. Followed by SO_2 (1066 $\mu g/m^3$), PM_{10} (681 $\mu g/m^3$), O_3 (653 $\mu g/m^3$), NO_2 (303 $\mu g/m^3$) and $PM_{2.5}$ (101 $\mu g/m^3$). The concentrations were much higher during the dry season compared to the wet season. Meteorological conditions including rainfall, temperature and humidity might have highly contributed to the significant decrease of the air pollutants concentration. The wind speed was generally very low suggesting that long distance pollutants transportation might have a low contribution to the air pollution. On the other hand, this is favorable to air pollutants accumulation.

The source contribution analysis results showed that anthropogenic activities mainly contributed to the air pollution. This associated to the local conditions and economic situation resulted in a poor air quality. Many developing cities face similar issues associated with the local conditions (underdeveloped infrastructure, low fuel quality and excessive biomass combustion for cooking and other daily activities) that worsen the air pollution. Also, the geographical location of Bamako city (surrounded by hills as aforementioned) might be a contributing factor to the very high level of pollution. In fact, this geographical location does not allow pollutants diffusion. Leading to air stagnation and therefore, pollutants accumulation. Moreover, we sus-

pect that thermal inversion which is a common phenomenon in Bamako might be one of the greatest factors influencing the pollutants' concentration variation and daily trends. Especially for O_3 and NO_2 that showed very particular trends and, PM showing higher concentration in the evening. Consequently, more attention should be given to the thermal inversion phenomenon in air pollution studies.

To sum up, the observed ambient air quality was highly affected by anthropogenic activities including traffic emissions and the use of biomass and biofuel. Factors such as local conditions and natural phenomenon contributed to the poor air quality. More studies are needed to support our findings and palliate to the lack of information in this region. Nevertheless, this study revealed very high the concentrations of the major air pollutants. The values far exceed the international and national standards for nearly all the pollutants [107] [13] [202]. Only CO presented lower values then the guidelines even though its concentration was very high. This suggest adverse health and environmental effects. Once more, our findings highlighted the necessity to promptly promulgate and apply mitigation strategies and air pollutants emission reduction strategies.

Air Pollution Perception Survey; city of Bamako

Nowadays, air pollution is one of the main global concerns. The release of tremendous air pollutants in the urban atmosphere from various anthropogenic activities lead to a continuous deterioration of the air quality. A bad air quality is considered as an important environmental risk factor. Depending on the pollutants type, air pollution can be invisible or perceptible. Either way, pollutants can be detrimental for human health and environment. Concentrations of these pollutants above the background level can result in serious health damaging effects. Many studies across the globe have proven the effects of air pollution on human health. Varying from minor effects such as allergic reactions, respiratory airways and eyes irritation and, asthma to major effects such as cardiovascular and respiratory diseases, lung cancer and even mortality. One of the most major adverse effects of air pollutants emission on environment is climate change. As a matter of fact, particulate matter can highly contribute to climate change. Either by solar light absorption resulting in a warming effect or through reflection by cloud condensation nuclei resulting in a cooling effect. In addition, air pollution can result in a decrease of the quality of life; unpleasant smells, visible dust and smoke can significantly affect a population life conditions.

Developing countries residents are the most vulnerable to air pollution adverse effects. In addition to health and agriculture, economy and lifestyle are also considerably affected. Burning charcoal, wood and oil for energy production result to a substantial air pollutants emission. Compared to developed countries, developing and underdeveloped countries have limited

resources and technologies to reduce air pollutants emissions and fight air pollution. These include less polluting household energy production, cleaner transportation and, more efficient waste management system.

Exploring the relationship between indoor and outdoor air pollutants emissions sources, anthropogenic activities and the population's knowledge on air pollution is important to control air pollutants emissions. Understanding the population mindset is a very important factor to consider in the promulgation of effective mitigation strategies. We believe that awareness is the first step towards addressing any issue. Once aware, it becomes easier to take a direction to make a contribution, change, or reach a goal. This could lead to successful outcomes in the efforts to reduce the air pollutants emissions and to concurrently, contribute to the efforts to protect public health.

The present survey on the perception on air pollution in the city of Bamako comes within this framework. It aimed to analyze the population's understanding on air pollution and its emission sources in urban areas. Especially the effects of their own daily activities on the air quality and the possible repercussions on health and environment. In the previous sections, specific anthropogenic activities (the indoor combustion of incenses and insecticides, the cooking fuel, and road traffic) were determined as main indoor emission sources hence, main exposure sources. Where; the importance of investigating the inhabitant's knowledge on these emission sources. This section also aims to investigate the population understanding of the health effects related to air pollution. This, from the experience and self-reported feelings of individuals. Many health issues are related to the exposure to air pollution. Hence, it is important to know how individuals perceive health effects on themselves and on their friends and relatives through personal experience. Furthermore, the questionnaire aimed to get information on whether or not air quality was affecting the inhabitants 'lifestyle. Air pollution in addition to the major aforementioned effects can have unpleasant effects such as bad smells, visibility reduction, dusty deposition on buildings and households and, respiratory discomforts. Finally, the questionnaire was useful in providing information on the population willingness to contribute to environmen-

tal problem-solving efforts. Their perception on the self-behavior and other local inhabitants' behavior towards facing air pollution issues.

To our knowledge this questionnaire provided the first data regarding the population awareness on air pollution in Bamako city. The results could be very useful for local government and organizations to formulate relevant plans to control air pollution and reduce the population's exposure. Moreover, the results can be a guide and a reference for future researches aiming to benefit environment and public health.

Questionnaire administration method

After evaluating the population personal exposure to $PM_{2.5}$ and characterizing the chemical composition of PM emitted from different anthropogenic emission sources in Bamako city, we conducted a survey of the population's perception on air pollution. This This consisted of administering a questionnaire to the residents.

The questionnaire was focused on the population's perception about air pollution and the possible resulting impacts. It prepared in French; the official language in Mali. It contained numerous questions and included four different sections (Table A.4). The first section investigated the relationships between typical daily activities and air pollution. The second section addressed the health status and medical history. For the third section, we investigated the population's perception and awareness on air pollution. The last section focused on exploring the population response to air pollution prevention and mitigation strategies.

The data was collected using the questionnaire. We had no restriction in the selection process (random selection). The survey was conducted at an individual level but included different age groups and professions. For children under 12, the agreement and assistance of an adult was necessary. Respondents were asked to answer all questions as honestly as possible.

The questionnaire was randomly distributed in the city of Bamako from 27, December 2021

to 05, January 2022. Nevertheless, we ensured the diversity in the age group and gender. 368 local inhabitants answered the questionnaire. Incomplete questionnaires were excluded from the data analysis. After removing these questionnaires, a total of 365 were validated.

3.5 The pollution perception on air pollution

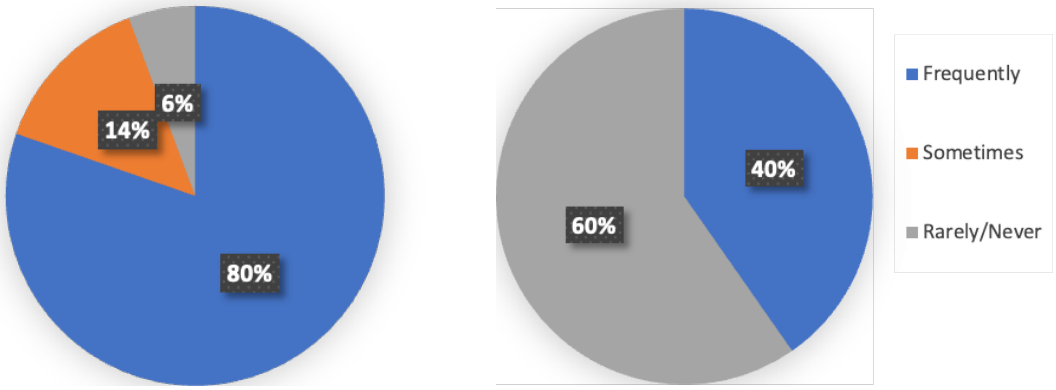
A total 365 were validated including 193 females and 172 males. Participants were between 9 and 80 years old. The questionnaire had four different sections. Namely; habits, health conditions and medical history, perception and knowledge on air pollution, prevention and mitigation. Theses sections respectively explored the relationship between daily habits and emission sources, self-reported health condition possibly related to air pollution, awareness on air pollution emission and, exposure sources and the reduction strategies. Below, are presented the findings from the survey.

3.5.1 Daily habits

Different daily common activities that emitted pollutants were investigated in this section. The first section explored the relationship between the common daily activities in households (cooking, indoor insecticide and incense products combustion), outdoor in traffic (during the commute) and, the air pollutants emission and exposure sources.

- **Cooking habits and behavior**

In Mali as in many other regions women are responsible of most of the household activities including cooking. As a matter of fact, the results from the survey clearly indicated that women were more involved in cooking then men. 80% of the female respondent frequently cooked, 14% were cooking sometimes and just 6% rarely cooked. Compared to female, the number of male participants that frequently cooked were twice lower. And more than half (60%) of the male participants rarely cooked. This indicated that women are more likely subject to emissions from cooking compared men (Figure 3.31).



(a) Female **(b)** Male

Figure 3.31: Cooking activity; female versus male

However, 78% of the respondents reported the presence of family (children, parents) and/or friends while cooking. During food preparation, family members and friends sometimes gather in the kitchen area to help each other and spend time together. This suggested that exposure occurring during the cooking time involves not only the cooks but also the family members and friends. This can be considered as part of the cooking behavior related to culture.

Furthermore, the results showed that charcoal and wood represented the main energy sources for cooking. The use of these fuels is more adapted to the lifestyle and more affordable (price wise and availability). But, they represent a source of household air pollution (Figure A.11).

- **Road traffic sector**

Pretty much all the participants had to commute for their daily activities such as work, school and shopping. Consequently, they were regularly in traffic (Figure 3.32). The traffic sector is one of the main outdoor exposure sources worldwide especially in developing countries. Several factors contribute to this; the higher traffic emissions from motorcycles and second-hand cars, the road conditions (mostly unpaved; FigureA.5), the fuel quality and so on. Figure A.12 confirms that in Bamako the traffic sector is mainly dominated by motor bikes followed by personal cars and public transportation. The higher number of motorbikes can be attributed to the facts that they are cheaper to purchase, easier to maintain and faster to commute during

traffic rush hours. Nevertheless, motorbikes are a major air pollution contributor as they emit higher quantities of unburned oils, significantly contribute to smog formation and, may contain more harmful compounds [203].

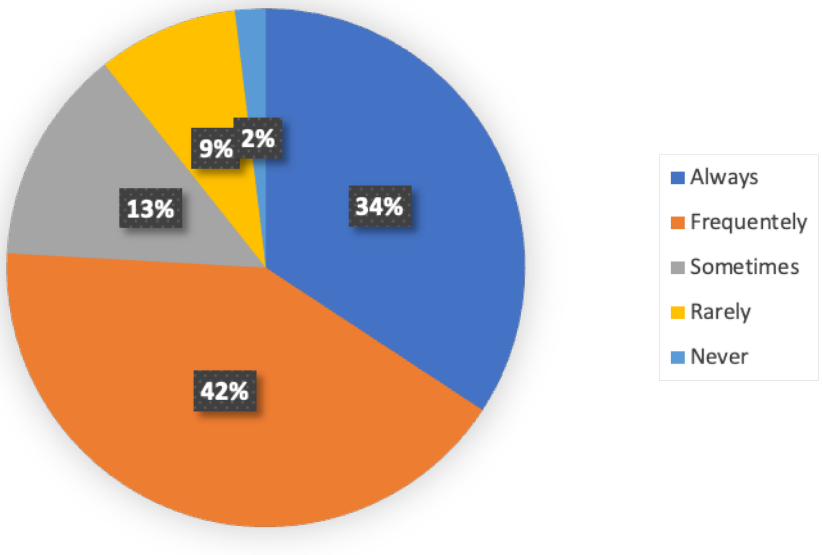


Figure 3.32: Traffic sector

In this study, 88% of the subjects reported the use of gasoline as fuel use in traffic and 12% reported the used of diesel. This could be due to the dominance of motorcycles in traffic; which mainly run on gasoline. Although both fuels are polluting, gasoline emit 80 times more carbonaceous PM than diesel [204].

Similarly, to the cooking activity, participants were frequently accompanied when they were in traffic. Respondents were usually with family members, friends or clients for public transportation drivers.

The use of public transportation can considerably reduce emission from traffic such as break and tire wears, engines emission, dust resuspension from traffic. But the public transportation system is underdeveloped in Bamako hence inconvenient for the local inhabitants. SOTRAMAs (Société des Transport du Mali) are not comfortable and have not fixed time schedules. Taxis are more comfortable but very expensive for the daily commutes. 62% of the respondents

preferred not to use public transportation. A more convenient and comfortable transportation system will encourage the inhabitants to use public transportation for the commute instead of motorbikes and personal cars.

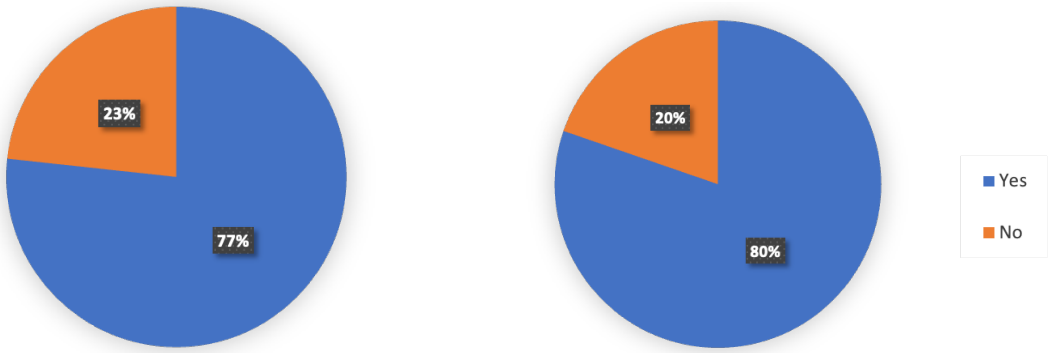
Additionally, we investigated the smoking habit. The results showed that only about 20% of the subjects were smoking. More than half of this percentage smoked only when they are alone. This percentage of none-smoking habit in the respondents might be due to the culture. Culturally, smoking is not perceived as a good behavior for most inhabitants.

- **Insecticides and incense products**

Insecticides and incense are widely used products over different regions and in different cultures worldwide. In these regions the products are used for different reasons including, religious practices, culture and tradition, mosquitoes' control.

Insecticides and incense combustion were daily common practices for the participants. 77% and 80% of the participants reported the use of ICS and IST respectively (Figure 3.33). According to the survey, the main reason for the use of ICS from the most important to the least in Bamako was to provide a nice scent around the houses, followed by cultural reasons and daily routine (Figure A.13a). The use of ICS for religious practices was insignificant in this region compare to other regions in Asia (Japan, India for instance) where, ICS is mainly use for religious reasons. The ICS used in Mali is traditionally made and the main heat source for the combustion was charcoal in traditional burners (over 60%), the rest of the respondents were using either electricity or steam (Figure A.14a).

IST was mainly used to repeal mosquitoes and prevent malaria (Figure A.13). The IST used in households was mosquito coils. The coils were combusted by lighting the tip of the coil or by using charcoal in traditional burners as for ICS (Figure A.14b). During the use of the products, the rooms were most often not aerated or had poor aeration. In general, the products users deliberately reduced the aeration conditions to maintain the smell of the incense or, the smoke released from the mosquito coils for a better effectiveness (repealing mosquitoes).



(a) Use of ICS **(b)** Use of IST

Figure 3.33: Percentage of respondents using ICS and IST products

These products have been previously reported as one of the greatest indoor particulate emission sources [100] [78]. The use of charcoal as combustion source and the aeration conditions might contribute to a high pollutant emission.

3.5.2 Health status and medical history

The survey included questions on the physical health status. The second section of the questionnaire, covered the adverse impacts on the physical health of the respondents that can be possibly related to air pollution. One third of the respondents reported health problems. Of this fraction, 82% did not know the cause of their sickness. 18% reported air conditions (such as haze and smoke) and, genetics (heredity) as causes. 41% of the self-reported illnesses were chronic disease and 13 % were acute (Figure 3.34). 15% of the respondents suffering from chronic diseases had lung cancers. The other individuals with chronic diseases suffered from; asthma, bronchitis, pulmonary diseases, rhinitis, and cardiovascular diseases.

The effects reported by the respondents (discomforts such as coughing, eyes irritation, respiratory obstructions and dizziness) occurred outdoors as well as indoors. And this, during different activities and in different microenvironments including the use of mosquito coils, the cooking activity, the commute (traffic sector), the workplaces, markets and even gyms.

In general, participants suffered from health issues varying from sneezing, eyes and throat

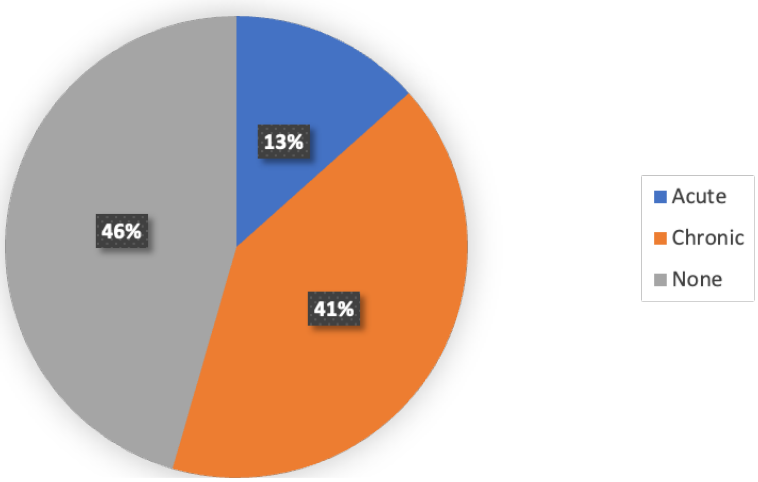


Figure 3.34: Health status of the respondents

irritation to respiratory problems (coughing, asthma) and even cancers. All the aforementioned conditions were associated to air pollution in previous researches [60] [62] [11]. This suggest that the air condition might be a main factor contributing to the health effects reported by the 82% of the subjects that did not know the cause of their health problems.

3.5.3 Level of awareness and air pollution mitigation

This section covers the two last sections of the questionnaire. The third section, focused on investigating the subjects' awareness and perception of air pollution. Including the emission sources, the exposure sources and the effects on health and lifestyle. The fourth section contained questions on the willingness of the respondents to contribute to the air quality improvement plans and the possible preventive measures in their point of view.

73% of the participants were aware of indoor and outdoor air pollution through visual and/or perceptible effects. 37% of participants speculated that they do not hear about air pollution and 63% have heard about air pollution from diverse information sources (Figure 3.35).

The most informative sources, mentioned by participants were institutions (schools, universities), television and radio.

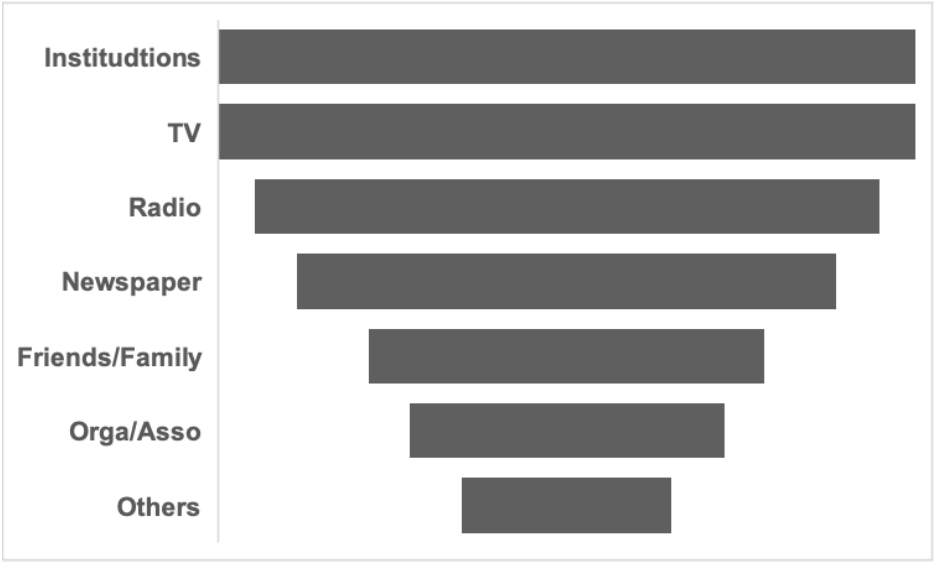


Figure 3.35: Sources of information. Orga: Organization; Asso: Associations

Each respondent was asked to choose the three most polluting activities from their perception. Road traffic, waste incineration, cooking and industrial emissions were the frequently mentioned pollution sources. With 21%, 15% respectively and for traffic and waste incineration. Cooking and industries were both 11% (Figure 3.36).

In Mali, industries are underdeveloped. Although they are considered as a main source of emission in different part of the world, considering the real characteristics of Bamako city, the order of the pollution sources from the most to the least polluting would be slightly different.

The probable three most outdoor pollution sources would be attributed to:

- Daily traffic; the elevated number of motor vehicles, the domination of second-hand cars and the unpaved streets conditions would result to a high emission of diverse gases and particulate.
- Dust re-suspension; considering the condition of the unpaved ground and local meteorological conditions (seasons for instance) dust re-suspension might occur from daily common activities such as walking and cleaning (sweeping the floor). Additionally, the harmattan event occurring during the dry season is favorable to PM transport from the north of the country (Sub-Sahara Desert).

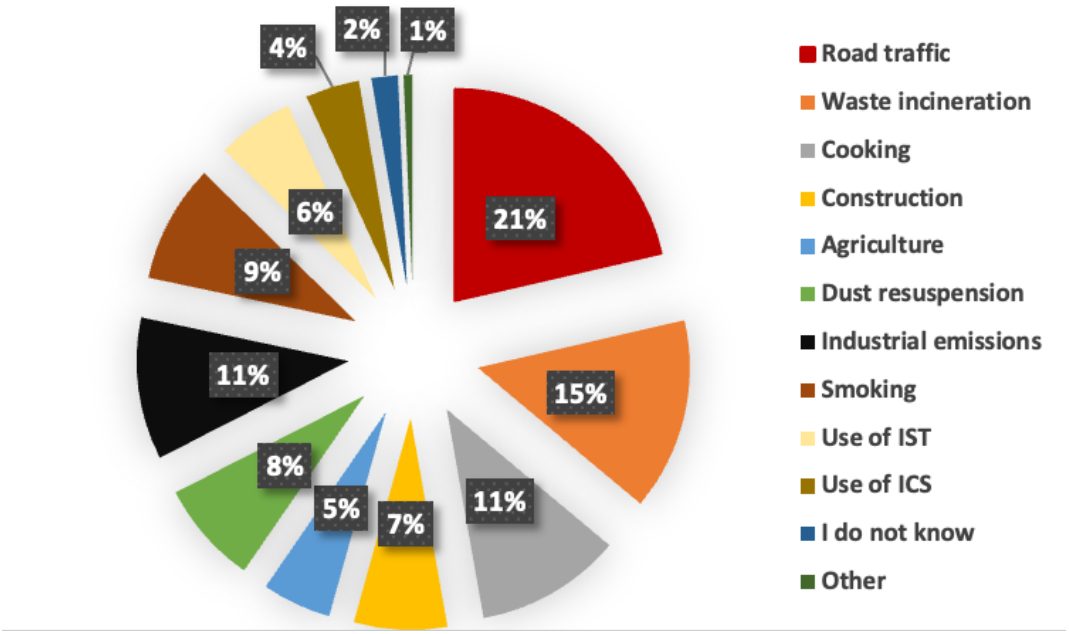


Figure 3.36: Contributing factors to indoor and outdoor air pollution from the respondents' perception

- The waste management through uncontrolled open air waste incineration is a very common practice in Mali. This technique considerably releases pollutants in the ambient air.

This section indicates that perception of the participants on outdoor air pollution might be slightly different from the real situation. The population's perception might be influenced by their daily experiences but also by the information sources. Road traffic and waste incineration are typical activities in the city. On the other hand, the respondents' perception on the industrial emissions might be influenced by the information sources rather than daily life experiences. Globally, a main source of air pollution, is attributed to industrial emissions. Especially in highly industrialized countries including China and United State. Information on air pollution in such region of the world is highly available on TV programs, media and institutions even in developing countries where, industries are not extensively developed. However, the actual air pollution sources in industrialized areas are different compared to the ones in less industrialized areas. This explains the perception of the participants regarding industries as one of the most prominent emission sources in Bamako city.

Indoor air pollution sources had small contribution on daily exposure according to the partic-

ipants perception. Yet, 80% and 77% of the participants were using insecticides and incense respectively in daily basis. IST and ICS combustion considerably emit PM. These activities were identified as indoor activities with the greatest PM emission and personal exposure sources. Furthermore, the exposure assessment for to IST and ICS indicated high risks in the previous sections (Health risk assessment). This demonstrated that the knowledge about IST and ICS as main exposure sources and possible health risks are not clearly understood.

The data presented in Table 3.18 refers to the percentages with respect to the overall responses.

Table 3.18: Perception and mitigation of air pollution

	Yes	No
Do you often hear about air pollution?	63	37
From your point of view , are you exposed to air pollution?	66	34
From your point of view, does IST use exposes you?	68	32
From your point of view, does ICS use exposed you?	54	46
From your point of view, does cooking use exposed you?	57	43
From your point of view , does road traffic exposed you?	61	39
From your point of view , does Smoking exposed you?	67	33
Does air pollution affect your health and/or lifestyle?	67	33
Did you or any of you acquaintances had/have problems from air pollution exposure?	42	58
Do you think air is polluted around you?	66	34
Do you think it is necessary to improve the air quality around you?	69	31
Do you want to contribute to mitigating air pollution?	65	35

Of the participants 66% felt that they were exposed to air pollution for diverse reasons related to the life condition in the city. Some subjects mentioned that they often have asthma crises related to the air quality. Many participants complained of gases emissions from the traffic sector and waste incineration. Indeed, participants who lived around traffic sites and waste discharges claimed to be constantly bothered with unpleasant air conditions. Dust re-suspension was also frequently mentioned. More than 40% have reported that themselves or their acquaintances were facing health issues related to the air pollution.

Nearly 70% believed that it was necessary to improve the air quality in their surroundings. They have reported unpleasant experiences (such as bad smells and irritations) in their daily lives. 65% of the subjects were willing to participate and cooperate in the efforts to improve the air quality they were exposed to. They suggested that the local government and responsible should take actions to improve the air quality. From their perception, providing access to cleaner household energy sources, planting more threes to reduce dust re-suspension and organize campaigns to increase the public awareness could help improving air quality.

This survey shows that the air condition exposes Bamako's inhabitants to health risks and affects their lifestyle. It also exposes them to health risks. Although some of the respondents had knowledge about air pollution, there is a lack of information on the air pollution emission sources and exposure risks .

3.5.4 Conclusion and recommendations

In this section, a questionnaire was administrated to 365 local inhabitants in the city of Bamako to investigate the perception and self-reported experiences regarding air pollution. The subjects reported discomforts due to air pollution and, the reported health condition might be related to the exposure to air pollutants. A considerable fraction of respondent suffered from chronic health conditions including cancers.

Our results indicate that the majority of the participants we surveyed were aware of air pollution. First because they were able to perceive it visually and smell malodorous emissions. Second, the number of participants often hearing about air pollution was higher than the number of participants who do not hear about air pollution.

Most participants believed they were exposed to outdoor gases emitted from vehicles engines in traffic, waste incineration and dust resuspension. And, in households from cooking especially using wood as combustion fuel. Few participants also mentioned the combustion of

insecticides and incense. The real outdoor and indoor pollution sources might differ from the real condition in the city. Suggesting that the lack of information and knowledge about the sources of air pollution. The age, gender, level of education did not have a high influence on the population's perception on air pollution sources and the information sources were unchanged. Even though a high percentage of the respondents had access to information on air pollution, a significant percentage were not aware of air pollution, their perception on air pollution was affected by personal daily experiences but also by information sources.. Proper information on air pollution exposure sources and adverse health effect should be properly communicated. More informative campaign should also be initiated to increase the awareness and knowledge of emission sources specific to the local circumstances. This can be realizable through institutions, TV, and radio. Many participants get information from the aforementioned sources. Therefore, the dissemination of accurate information on the real emissions and exposure through these sources could be useful.

The air quality was affecting most of the participants' daily lives. Many participants complained from discomforts and self-reported effects such as eyes irritations and respiratory disorders (coughing and asthma). Moreover, a significant number of participants suffered from illnesses including pulmonary diseases and lung cancers. Numerous previous researches have associated these diseases to the exposure to air pollutants. This indicate the alarming level of air pollution in the city.

It is very important that the local government and organizations include the local inhabitants in the in the pollution control plan. From this survey, local inhabitants are open to contribute to the efforts in improving air quality. They believed the local government and organization in charge should implement strategies to improve the air condition. And, would like to be involved in the air quality improvement efforts. Laws and restrictions on air pollution emissions should be enforced and communicated to the local population in addition to disseminate information widely on air pollution and its effects. Furthermore, possible reduction and exposure mitigation strategies applicable at individual levels are recommended. The current pandemic showed that

daily habits can change through communication. Wearing masks was not popular in Bamako. Due to the COVID 19 outbreak , many local inhabitants were wearing masks as preventive and risk reduction measures. Such behaviors should be encouraged not only for the COVID19 pandemic period but also for reducing exposure during daily common activities. Wearing mask could significantly reduce exposure from traffic and outdoor dust re-suspension.

The willingness of the local inhabitants to collaborate could be an asset in improving air quality in the city of Bamako and should be highly considered in mitigation plans. Organizations and local governments should also consider strengthening laws and regulations on the importation of bad quality fuels, the aging vehicle fleet, the cooking fuel and stoves. Additionally, it is important to improve and encourage the use of public transportation. Such recommendation was given in detail in the previous section.

Chapter 4

General conclusion

Over the years, air pollution has become one of the major concerns worldwide. Humans rely on the environment for all of our daily needs. It is therefore natural that we release tremendous chemicals into the atmosphere. We inadvertently alter our living environment to address these needs. This results to adverse multiple effects on health and environment. Nowadays, the level of air pollution is high in many regions of the world. Considerable efforts have been made to reduce air pollution. These include scientific studies providing information on the origins and impacts of indoor and outdoor air pollution. Extensive researches have been conducted in developed countries where information is widely available. But, in developing countries including Mali, information is still very lax. Research is highly needed in these regions. This thesis on the study of air quality in the urban city of Bamako, falls within this framework. It aimed to provide information on the level of exposure to $PM_{2.5}$ in the individuals living in Bamako. Determine the relationship between the exposure level and common anthropogenic activities and investigate the health risks associated with the exposure to PM. In addition, this research aimed to provide information on the concentration of criteria air pollutants in the ambient air and identify the emission sources. Finally, this work investigated the perception of the population on air pollution.

The first section of the findings presented the personal exposure to $PM_{2.5}$ in Bamako's inhabitants. The concentration exceeded the World Health Organization's (WHO) exposure standards in indoor and outdoor microenvironments. Palm size optical $PM_{2.5}$ sensors provided the mass concentration of $PM_{2.5}$ (in $\mu g/m^3$) during the common daily activities. The participants wore the sensors on their chest for at least 3 days between September 2020 to February 2021. The exposure levels in four different groups of residents were investigated in relation to their daily activities. The group of office workers (OW), the group of students (ST), the group of drivers (DRI) and the group of cooks (COOK). A variation in $PM_{2.5}$ concentration was observed during different activities and in different microenvironments. The main exposure sources were identified. The highest average 10 min concentrations were observed at home and in bedrooms, while the participants were using specific products that included insecticides (IST; 999 $\mu g/m^3$) and incense (ICS; 145 $\mu g/m^3$). IST was used to repeal mosquitos and ICS was mainly used to provide

a nice scent around the house as part of the Malian culture. The use of these products was common in the participants daily lives. These were followed by the traffic sector (216 $\mu g/m^3$) and cooking (150 $\mu g/m^3$). The lowest average 10 min concentrations were also observed in the same microenvironment lacking IST or ICS ($\leq 14 \mu g/m^3$). With no use of specific products, OWs and STs were the least exposed, and DRIs and COOKs were the most exposed. The daily concentrations in the participants were substantially high compared to the WHO's yearly and daily recommended exposure levels of 10 $\mu g/m^3$ and 25 $\mu g/m^3$. Up to 7.7 and 3 times higher respectively.

Second, the chemical composition analysis of PM emitted from the greatest exposure sources indicated the difference in PM composition from different sources, the health risks and the source contribution. PM was collected at different typical anthropogenic emission sources indoor as well as outdoor. Samplings were also carried in households during the combustion of insecticide and incense in households and the cooking activity using charcoal and wood fuel. The outdoor microenvironment was a typical roadside characterized by an intense traffic. The chemical characterization involved ions, carbonaceous ; organic carbon (OC) and elemental carbon (EC) and, heavy metals. The results revealed that ICS and IST were dominated with anions whereas cooking with charcoal fuel, cooking with wood fuel and roadside samples were dominated with cations. OC and EC values suggested that all the emission sources were mainly characterized by incomplete combustion. Additionally, the US EPA health risks assessment evaluation methods were used to investigate the non-carcinogenic risks Hazard Quotient (HQ) and Hazard Index (HI) and, the carcinogenic risks (CR) calculated from the toxic metals concentration. The results indicated higher HI values than the recommended limit of 1 for nearly all the emission sources. The values were ≤ 6.04. Similarly, CR values were higher than the lower boundary limit (1E-6). In general, the HI and the CR indicated unsafe values for human health. The risk was higher in children than adults. The CR exceeded the unacceptable limit in children for cooking using wood fuel and the use of ICS. Public transportation drivers were the most at risk in the traffic sector. The indoor microenvironments presented greater health risks compared to the outdoor microenvironments. Furthermore, the source apportionment was per-

formed using the mass chemical balance (CMB) and the principal component analysis (PCA) technique. The results showed that soil dust resuspension and biomass combustion highly contributed to the PM pollution. The enrichment factor (EF) analysis indicated a high influence of anthropogenic activities to the concentration of heavy metals. The metals highly available on the earth crust were dominant. This was attributable to the fact that the streets were mostly unpaved and dry. This findings demonstrated the importance of the infrastructure development in the air condition of an urban area.

Moreover, the hourly, daily and monthly concentration variation of major ambient air pollutants including NO_2, O_3, SO_2, CO, $PM_{2.5}$, PM_{10} were determined. The data was collected at one of the meteorological stations of Mali in Bamako city from February to August 2021 using Vaisala AQT400 air quality monitor. The pollutants presented very high concentration especially during the dry season. CO presented the highest mean concentration over the 6 months sampling period (2974.59 $\mu g/m^3$) followed by SO_2 (1066.09 $\mu g/m^3$), PM_{10} (681.42 $\mu g/m^3$), O_3 (652.91 $\mu g/m^3$), NO_2 (302.66 $\mu g/m^3$) and $PM_{2.5}$ (101.14 $\mu g/m^3$). Concentrations notably deceased from the dry season to the rainy season. The principal component analysis indicated a high influence of anthropogenic activity on the air condition. The local conditions also had influence on air quality. The low wind speed might have contributed to air pollutant stagnation during the dry season and, the rain might have contributed to a decrease of the air pollutants concentration during the rainy season.

The last section of the results focused on investigating the perception on the population on air pollution. A survey was administrated to 365 inhabitants. The results indicated that the air condition in Bamako city was unpleasant to the residents. Although the respondents were aware of air pollution, their perception might be influence by information sources that are not proper to the local situation. The health issues reported by the respondents such as asthma, pulmonary diseases and lung cancers could be the result of the exposure to a poor air quality in a daily basis. The respondents, would like the air quality around them to be improved. They were willing to collaborate and contribute to the efforts of the local governments and organizations

in improving the air quality. At the end of this research, we can state that we have achieved our main goals in terms of providing information on the air pollution emissions sources and the exposure in the city of Bamako. This work advanced our understanding on the level and sources of air pollution as well as the associated health risks. The level of exposure was the highest in households during the indoor combustion of IST and ICS and during the cooking activity. Outdoor air pollution for traffic sites mainly generated from dust resuspension and biomass combustion. The risk assessment revealed the toxicity of PM. This constitutes a real risk for the health of the population. The information provided in this research will be a reference for future studies and could be useful for the local government and organizations in their effort to improve the air quality and protect public health. Moreover, this study was useful to increase the awareness of the local population on air pollution. As a matter of fact, in addition to the information provided in this research, the involvement of the inhabitants for the data collection has aroused their curiosity regarding air pollution.

Bamako's inhabitants are exposed to a high air pollution resulting in health risks. In addition to the non-carcinogenic and carcinogenic health risk assessment study in this research, toxicological studies involving cells exposure (in vitro culture) to the PM emitted from the main exposure sources will be valuable. Furthermore, it is necessary to conduct a regular air quality control at different sampling sites and initiate a long-term air quality monitoring to provide more information on the air pollution phenomenon in the city.

To sum up, this research demonstrated the complexity of air pollution in Bamako city. Typical anthropogenic activities were the main emission sources resulting to an acute exposure of the population to air pollution. The exposure sources were strongly related to the life condition, resulting in an acute exposure. This study highlights the importance of indoor air pollution sources related to culture and confirms previous studies on urban outdoor air pollution sources, especially in developing countries. The findings could be applied to cities other than Bamako, as similar practices and lifestyles are common in different cultures. It is necessary to promptly elaborate and apply effective mitigation strategies to improve air quality and protect public

health in this region. It is important that local government takes measures to reduce the residents' exposure and protect public health. Dust resuspension which was one the main ambient air pollution sources can significantly decrease with the improvement of the infrastructure such as constructing more paved streets. Law and regulations are very powerful tools for controlling activities deteriorating the environment. In Mali, there is an important deficit of legislation and regulation measure regarding environmental protection. Revising the laws and regulation on the fuel quality and the vehicles' technical inspection could reduce traffic emissions. Furthermore, developing a better waste management system instead of uncontrolled open-air incineration is essential. Gradually switching inefficient cooking stoves to more efficient ones and, elaborating plans to facilitate the access to cleaner household energy for cooking could greatly reduce households' emissions. Besides, individuals could manage their own exposure through daily actions such as using mosquito nets instead of mosquito coils, reducing the use of incense and properly aerating indoor microenvironments. Air is one of the most important natural resources. We consume more air than we drink and eat. Developing regions are the most affected by air pollution nevertheless, controlling air pollution is a common effort to which all countries shall be engaged. Because, Protecting the atmosphere is protecting the environment.

Protecting the atmosphere is protecting health.

Protecting the atmosphere is saving lives.

Protecting the atmosphere is preparing a better future for the next generation.

Protecting the atmosphere is everyone's responsibility.

Together let's protect our atmosphere !!!

Appendix A

Appendix

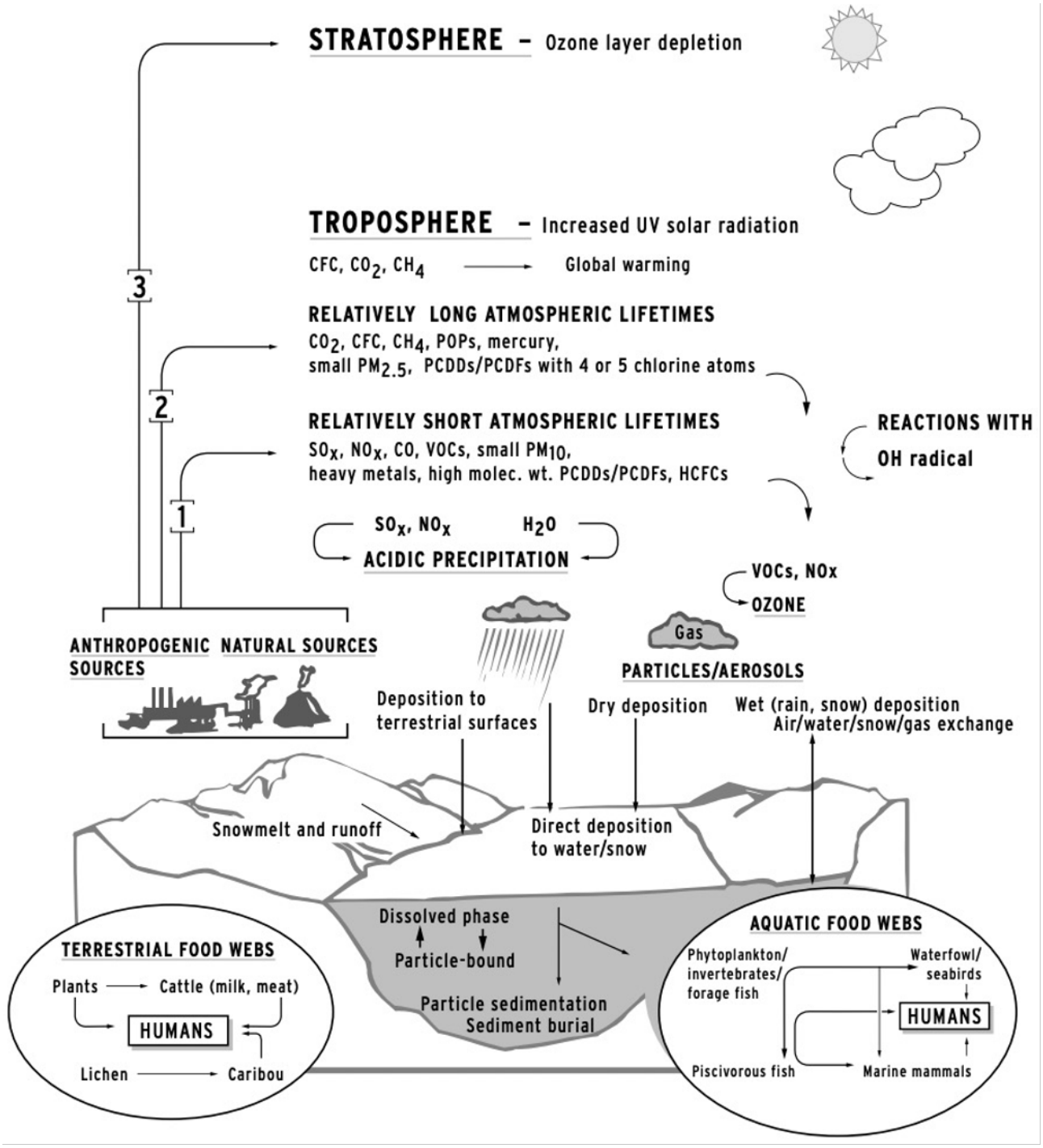


Figure A.1: Fate of pollutants in the lower atmosphere (troposphere and stratosphere). Adopted from [6]

Table A.1: Selected major chemicals that are medium to long-lived air pollutants emitted in cities (in alphabetical order), their source, health and environmental effects and scales of impact whether they have are a major contributor (•) to air pollution problems at the given scale or a minor contributor (◦)

Compound	Major emission sources in urban areas	Impact on human health	Impact on environment and infrastructure	Scales of major concern				
				Indoor	Local	Urban	Regional	Global
Carbon dioxide (CO_2)	The major product emitted during all fuel combustion. Also released by respiration of humans, animals, vegetation and soils.	Even high concentrations not toxic, but high density can accumulate in basements and poorly ventilated rooms and reduce / displace oxygen.	Most important long-lived greenhouse gas – alters global radiative forcing and therefore driver of anthropogenic climate change	•				◦
Carbon monoxide (CO)	A primary pollutant from oxygenlimited (incomplete) combustion in motor vehicles, industrial processes and domestic heating.	Interferes with absorption of oxygen by haemoglobin resulting in oxygen deprivation. Low-to-moderate dosages cause headaches, impair brain functions and reduce manual dexterity. At high concentrations death ensues. Heavier than air.	Affects animals the same way as humans. Contributes to formation of the greenhouse gases CO2 and O3 when oxidized	•	•	•		◦
Nitrogen oxides (NO, NO_2)	Primary and secondary pollutant resulting from fuel combustion in motor vehicles, coal-, oil-, and gas-fired power stations, industrial boilers and waste incinerators. Minor emissions occur naturally from soils.	Acute exposure causes respiratory diseases (coughs, sore throats) and at high concentration inflames airways and reduces lung functioning. Can aggravate bronchitis, asthma and emphysema.	Contributes to the eutrophication of aquatic ecosystems.	•	•	•	◦	
Ozone (O_3)	Secondary pollutant formed in urban areas primarily from VOCs and NOx, but also CH4 and CO can play a role in O3 formation at larger scales.	Damages respiratory tract and impairs lung function. Physical activity increases the dosage. Long-term exposure may result in decreased lung capacity and premature mortality.	Higher concentration can damage vegetation leading to reduced plant growth. O3 is a short-lived greenhouse gas changing radiative transfer in the troposphere.			•	•	
Sulphur dioxide (SO_2)	Primary pollutant emitted during combustion of sulphur-containing fuels (coal, diesel, fuel oil), and in industrial processing	Exacerbates asthma causing wheezing, shortness of breath and coughing and inflammation of respiratory tract. Synergistic effects with exposure to O3 and particulate matter.	Damages buildings. Causes acidification of soils and aquatic ecosystems downwind of emissions, can damage forests ecosystems. Contributes to the formation of particulate matter.		•	•	•	
Particulate matter (PM_{10}, $PM_{2.5}$, UFP)	Emitted as primary pollutant during combustion (low-temperature fires, diesel vehicles, waste incinerators, domestic heating and cooking), released during mechanical abrasion (road dust, construction) or formed as secondary pollutant from SOx, NH3 and NOx.	Can reach sensitive parts of the respiratory system. Exposure to fine particulates reduces lung function, increases cardiovascular and respiratory diseases and may cause premature mortality.	Changes radiative transmission in atmosphere (Chapter 5), can impact cloud droplet size distribution (Chapter 10) and alter radiative forcing on global scale. When deposited on snow and ice surfaces, changes their albedo.	•	•	•	•	•

Table A.2: Personal information collection sheet for participants

Groupe												Date
Numéro de capteur	Nom	Prénom	Age	Sex	Occupation	Quartier de résidence	Lieu de travail/ d'étude	Moyen (s) de transport	Fumeur/non-fumeur	Activité(s) sportive (s)	Numéro de téléphone et/ou mail	Signature

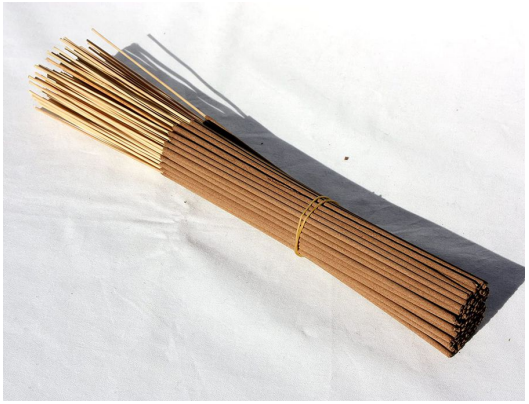
Figure A.2: Appearance of ambient air monitors Vaisala series AQT400

Figure A.3: Image of school situation: (a) students in class group 2, (b,c) schoolyard. © Alimata Dienta

(a) Three most popular insecticides in Mali

(b) Japanese insecticide

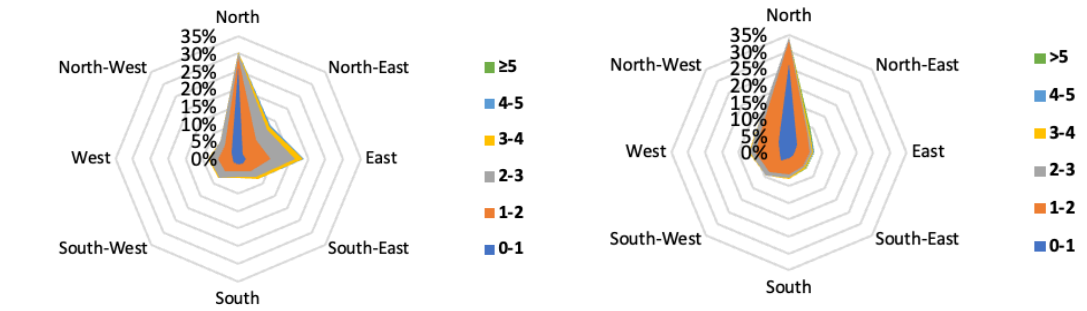
(c) Malian Incense. © bamada.net



(d) Japanese Incense. © verywellmind

Figure A.4: Different insecticide and incense products from Mali and Japan

Figure A.5: Images roadside sampling site (Malinium Pictures) area.
© Malinium Pictures



(a) Dry Season

(b) Wet Season

Figure A.6: Wind rose over the sampling period. Dry season; February to May and Wet season; Jun to August

Table A.3: Average concentration of metals for different emission sources composition (values are in ng/m^3). IST: insecticides, ICS: Incense. nd was used for samples having lower values then the blank samples

	Insecticide	**Incense**	**Roadside**	**Wood cooking**	**Charcoal cooking**
Li	3.12E+00	5.19E+00	4.64E+00	1.52E+01	1.11E+01
Be	1.51E+00	1.50E-01	4.10E-01	2.54E+00	1.66E+00
Na	1.58E+03	4.16E+03	3.46E+03	1.25E+04	7.76E+03
Al	3.47E+03	1.34E+04	2.25E+04	3.68E+04	2.09E+04
K	1.20E+04	1.47E+04	4.17E+03	8.41E+04	1.80E+04
Ca	9.02E+02	3.58E+03	2.44E+03	1.52E+04	1.04E+04
Sc	nd	1.25E+00	4.84E+00	4.76E+00	2.15E+00
V	8.21E+00	2.29E+01	5.79E+01	7.20E+01	3.66E+01
Cr	1.51E+01	6.56E+01	7.60E+01	9.53E+01	5.59E+01
Mn	4.26E+01	2.34E+02	2.10E+02	7.02E+02	4.12E+02
Fe	2.78E+03	1.09E+04	2.26E+04	2.88E+04	1.68E+04
Co	5.40E-01	4.62E+00	6.48E+00	1.23E+01	5.79E+00
Ni	2.39E+00	1.77E+01	1.68E+01	3.83E+01	5.95E+01
Cu	1.37E+01	1.90E+01	2.71E+01	7.14E+01	3.23E+01
Zn	1.64E+02	2.47E+03	1.11E+02	1.24E+04	5.25E+03
Ga	1.92E+01	3.75E+01	3.75E+01	1.58E+02	7.08E+01
As	3.14E+00	3.03E+00	4.80E+00	7.06E+00	4.79E+00
Se	7.90E-01	nd	1.56E+00	1.71E+01	3.00E-01
Rb	8.00E+01	5.09E+01	1.63E+01	2.23E+02	5.65E+01
Sr	3.24E+01	1.64E+02	6.65E+01	7.17E+02	3.54E+02
Y	nd	nd	3.75E+01	7.20E+01	nd
Mo	1.85E+01	nd	9.44E+00	nd	nd
Ag	nd	nd	1.70E-01	4.40E-01	1.50E-01
Cd	4.09E+00	1.44E+00	4.80E-01	3.69E+00	1.43E+00
In	nd	3.00E-02	4.00E-02	1.20E-01	8.00E-02
Sb	1.08E+00	4.78E+00	3.66E+00	7.85E+00	4.46E+00
Cs	2.56E+00	1.20E+00	7.60E-01	4.24E+00	1.57E+00
Ba	8.91E+01	1.69E+02	1.58E+02	7.22E+02	3.17E+02
Hg	nd	nd	nd	nd	nd
Ti	8.94E+00	2.11E+00	1.20E-01	7.73E+00	1.48E+00
Pb	4.76E+01	4.04E+01	2.02E+01	2.75E+02	8.80E+01
Bi	2.17E+00	2.00E-02	1.20E-01	nd	nd
Th	3.00E-01	7.40E-01	3.78E+00	4.94E+00	nd
U	1.80E+00	nd	1.03E+00	1.00E+00	nd

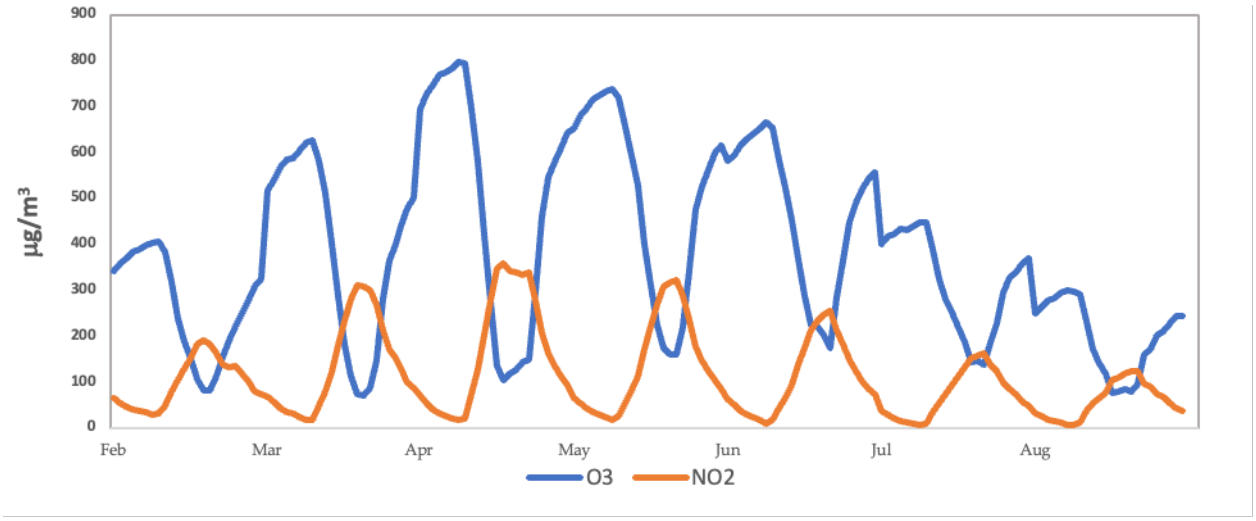
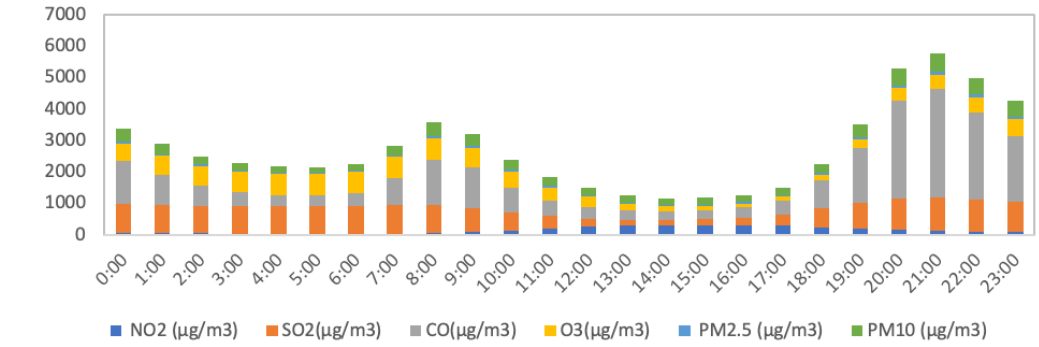
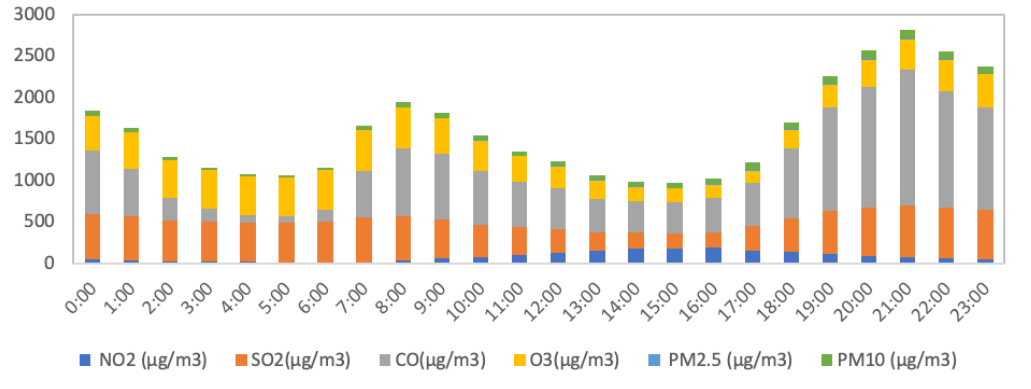


Figure A.7: NO_2 and O_3 trends from February to August 2021



(a) Dry Season



(b) Wet Season

Figure A.8: Hourly variation of the major pollutants from February to August 20

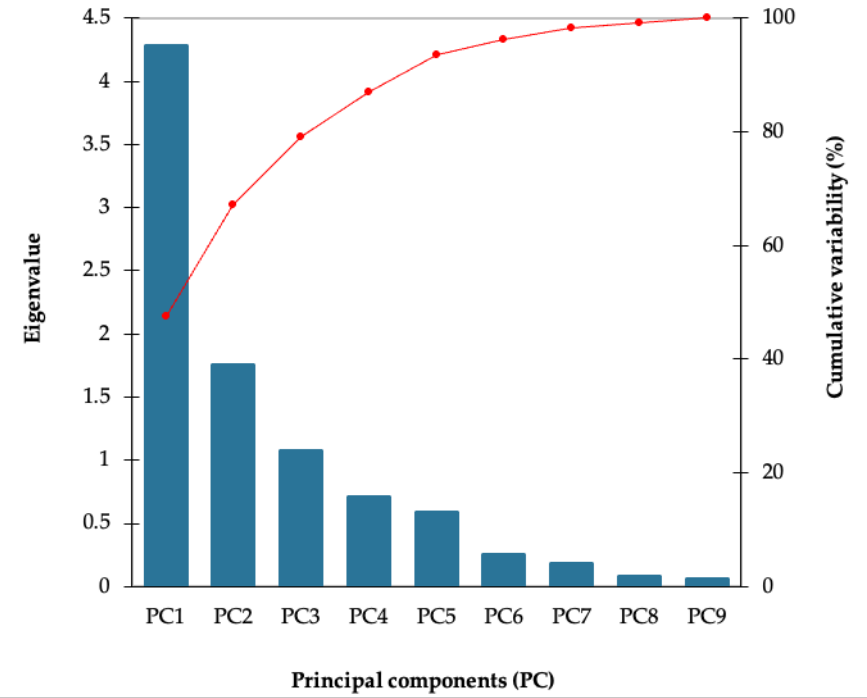


Figure A.9: Graphic representation of the principal components

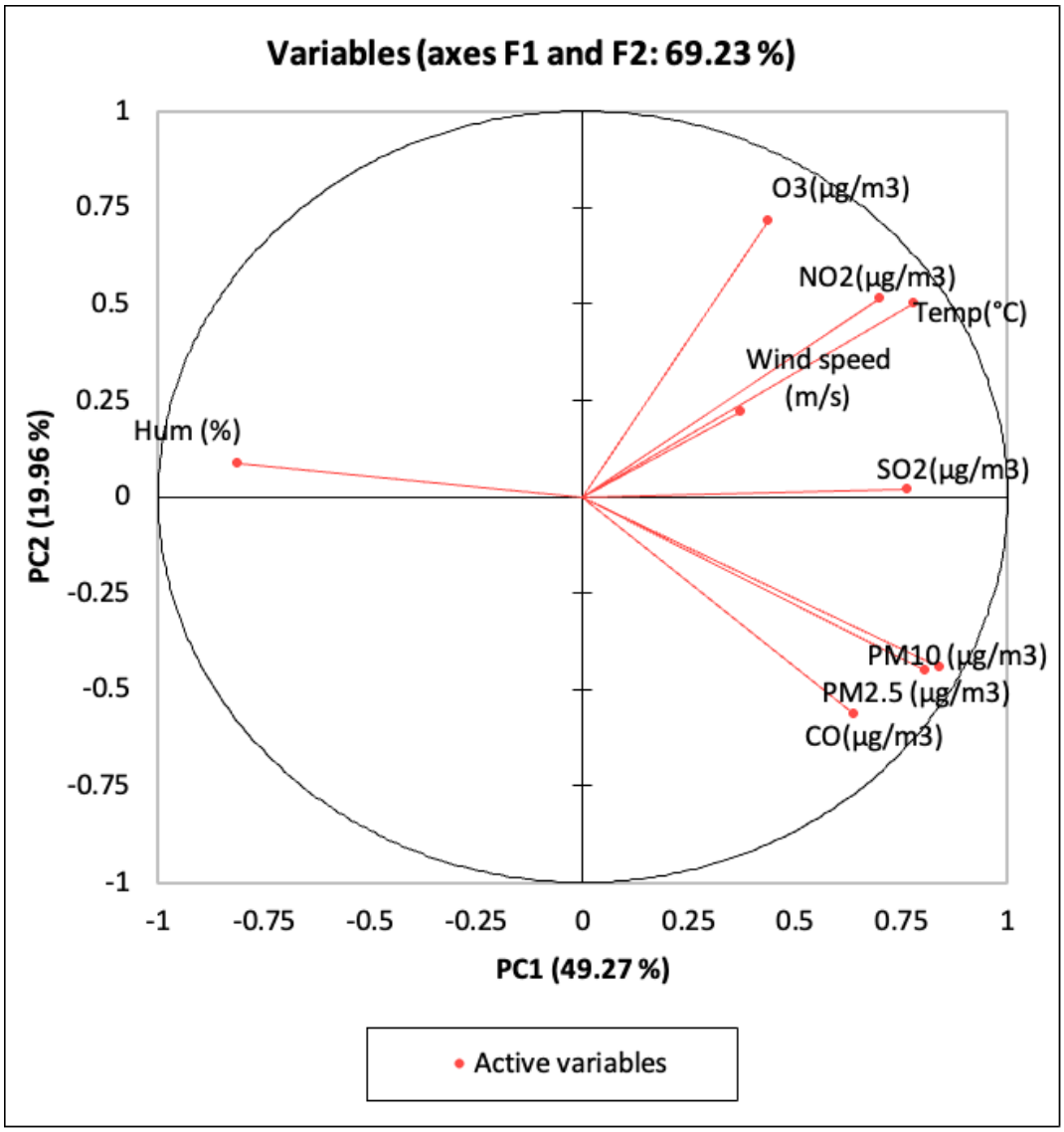


Figure A.10: Projection of air pollutants and meteorological elements on the principal components area of PC1 and PC2

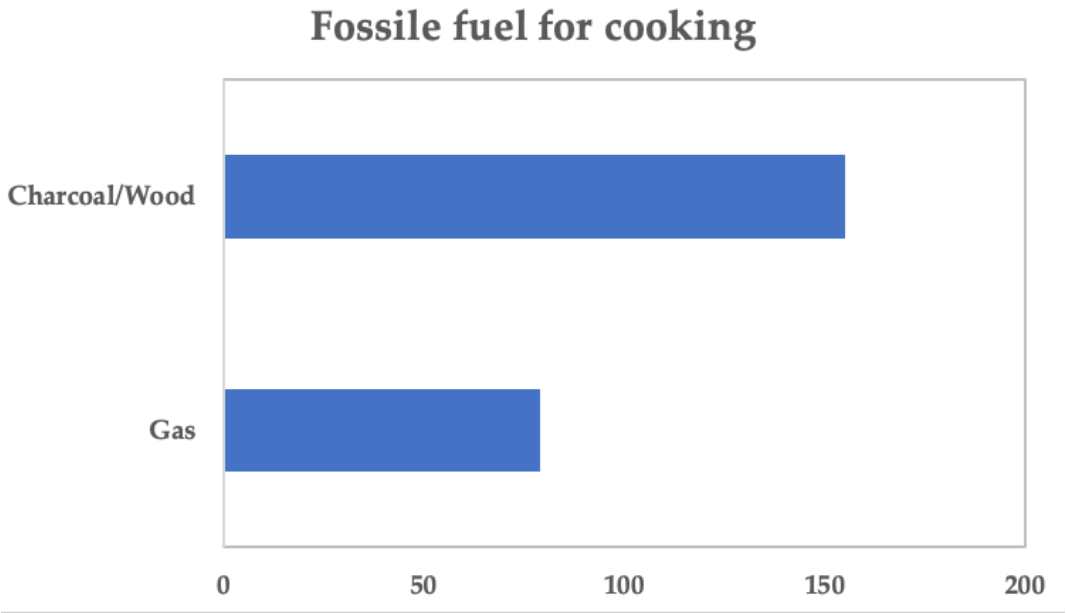


Figure A.11: Cooking fuel; Charcoal and Wood Vs gas

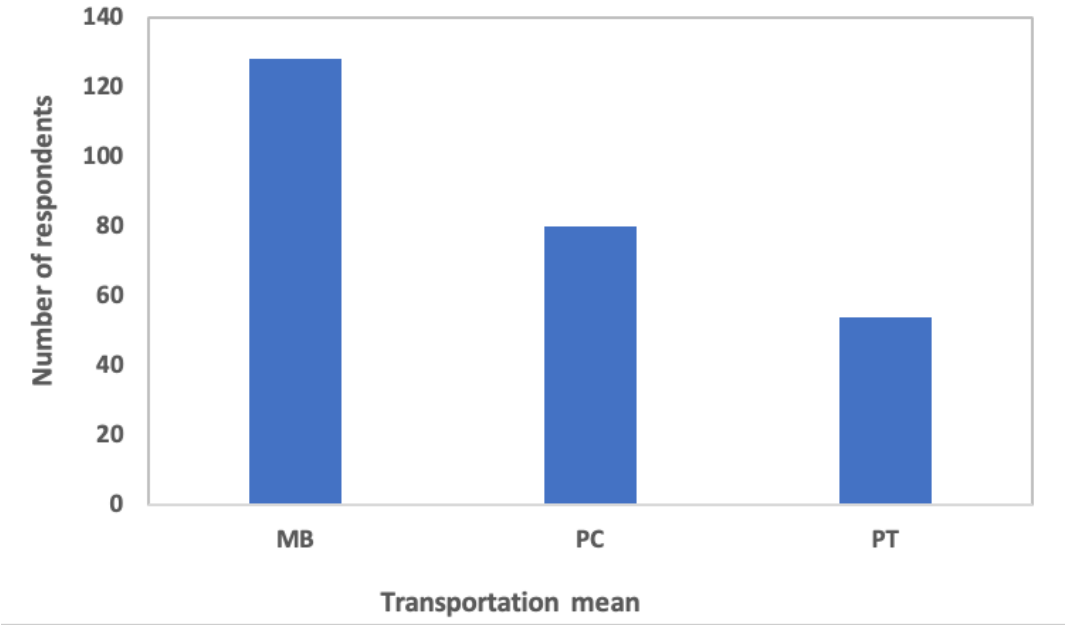
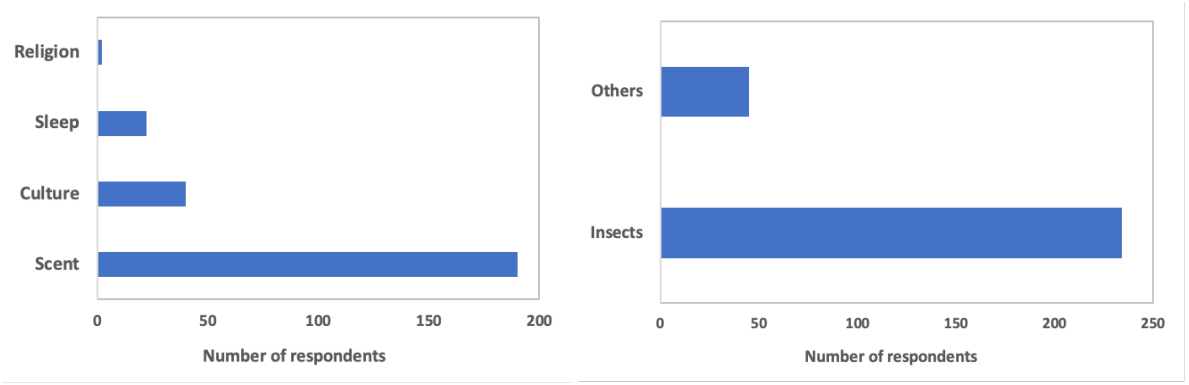
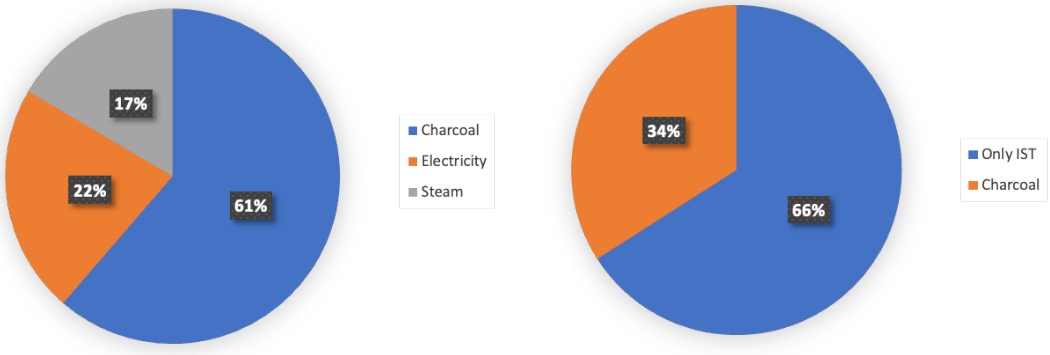


Figure A.12: Different transportation mean. MB: Motorbike; PC: Personal car; PT: Public transportation



(a) ICS **(b)** IST

Figure A.13: The different reasons for ICS and IST combustion



(a) ICS **(b)** IST

Figure A.14: Heat source for ICS and IST combustion

Questionnaire

Enquête de perception sur la pollution de l'air Cas de Bamako-Mali)

Date: Occupation: Numéro de questionnaire: Age:

Gendre (M/F) : Signature :

Instructions : Veuillez s'il vous plait cocher(x)

pour indiquer votre réponse le plus honnêtement possible.

Tjr: Toujours, Fqt: Fréquemment, Pfs: Parfois, Rrt: Rarement, Jms: Jamais

Habitudes		Tjs	Fqt	Pfs	Rrt	Jms
1	Cuisinez-vous ?					
1.2	Si oui (1), *Veuillez encerclez la (les) réponse (s) en gras et indiquer la fréquence.* Utilisez-vous ? (1) charbon (2) bois (3) gaz (4) autres					
1.3	Si oui (1), êtes-vous à proximité de quelqu'un quand vous cuisinez ?					
1.4	Vous trouvez-vous à proximité d'une personne qui cuisine ?					
1.5	Si oui (1.3 ou 1.4), *indiquez votre relation avec cette personne.....*					
1.6	Aider-vous vos parents à cuisiner ?					
1.7	Aider-vous vos parents dans les tâches ménagères ?					

Continued on next page

Table A.4 – continued from previous page

1.8	Rester-vous à la maison après l'école ? *Veuillez indiquer la (les) activité (s)*					
1.9	Si non (1.8) veuillez indiquer l'endroit (s) et l'activité (s)					
2	Vous trouvez-vous en circulation routière ?					
2.1	Si oui (2), êtes-vous accompagné ?					
2.2	Si oui (2.1), *veuillez indiquer votre relation avec l'accompagnant (s)*.....					
2.3	Quel est votre moyen de transport ? (1) Transport publiques (SOTRAMA, taxi etc.) (2) Voiture personnelle (3) Moto (4) autre (s).....					
2.4	Quel est le type de carburant que vous utilisez ?.....					
2.5	Si vous avez le choix, utiliseriez-vous les transports publiques ? (1) Oui (2) Non. Veuillez indiquer la raison de votre réponse					
3.	Fumez-vous ?					
3.1	Si oui (3), vous trouvez-vous à proximité d'autres personnes quand vous fumez ?					
3.2	Vous trouvez-vous à proximité d'une personne qui fume ?					
3.3	Si oui (3.1 ou 3.2), *veuillez indiquer votre relation avec cette personne*					
4.1	Indiquer le moyen de combustion.*Veuillez encerclez la (les) réponse (s) en gras et indiquer la fréquence*.(1) Charbon (2) électricité (3) autre.....					

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Table A.4 – continued from previous page

4.2	Pour quelles raisons utilisez-vous de l'encens?					
4.3	Restez-vous dans la même pièce (lieu) lors de l'utilisation ?					
4.4	Si oui (4.3), la pièce (le lieux) est-elle aérée ?					
5.	Utilisez-vous les insecticides ? ou, vous trouvez-vous dans une pièce où les insecticides sont utilisés ?					
5.1	Si oui (5), Veuillez encerclez la (les) réponse (s) en gras et indiquer la fréquence. **(1) spirale anti-moustique (2) spray anti- moustique (3) autres**					
5.2	Si spirale anti-moustique, veuillez indiquer le moyen de combustion. Veuillez encerclez la (les) réponse (s) en gras) et indiquer la fréquence. (1) en allumant l'extrémité de la spirale (2) au Charbon (3) autre					
5.3	Si oui (5), pour quelles raisons utilisez-vous des insecticides					
5.4	Restez-vous dans la même pièce (lieu) lors de l'utilisation ?					
5.5	La pièce (lieu) est-elle aérée ?					
État de santé et antécédents médicaux			Oui		Non	
6.	Avez-vous actuellement un (des) problème (s)de santé ou, aviez-vous eu un problème un (des) santé dans le passé?					
6.1	Si oui (6), veuillez spécifier la (les) maladie (s)					

Continued on next page

Table A.4 – continued from previous page

6.2	Si oui (6), Veuillez encerclez la (les) réponse (s) en gras) **(1) Aigue (2) Chronique**		
6.3	Connaissez-vous la cause de votre maladie?		
6.4	Si oui (6.3), veuillez spécifie.....		
6.5	Avez-vous déjà ressenti des malaises ?veuillez encercler la (les) réponse (s). (1) Toux (2) irritation des yeux (3) inconfort ou difficulté respiratoire 4) autres .....Veuillez indiquer l'endroit (s) et ou l'activité (s)		
Perception et état de connaissance sur la pollution de l'air		Oui	Non
7.	Entendez-vous parler de la pollution de l'air ?		
7.1	Si oui (7), *Veuillez encerclez la (les) réponse (s) en gras*. **(1) télévision (2) radio** **(3) journaux (4) amis et/ou famille** **(5) associations/groupes environnementaux (6) autres**		
8.	Pensez-vous que l'air intérieur est pollué ?		
8.1	Pensez-vous que l'air extérieur est pollué ?		
8.2	Si oui (8 ou 8.1). Pour quoi le pensez-vous ? Veuillez encerclez la (les) réponse (s) en gras **(1) Visuel (2) Ressenti(3) autre**.....		

Continued on next page

Table A.4 – continued from previous page

9.	Pensez-vous être exposé à la pollution de l'air ?		
9.1	Sioui(9),*veuillez indiquerle(s)lieu(x)*.Ex(travail,maison circulationetc.).....		
10.	Pensez-vous être exposé lors de l'utilisation des insecticides dans les ménages et ou autres endroits ?		
11	Pensez-vous être exposé lors de l'utilisation de l'encens dans les ménages et ou autres endroits ?		
12.	Pensez-vous être exposé à la pollution pendant la cuisine ?		
13.	Pensez-vous être exposé en circulation routière ?		
14.	Pensez-vous que fumer ou être près d'une personne qui fume vous expose à la pollution ?		
15.	Pensez-vous que la pollution de l'air peut ? affecter votre santé et/ou style de vie ?		
16.	Est-ce que vous ou quelqu'un que vous connaissez avez déjà eu des problèmes de santé liés à la pollution de l'air ?		
Prévention / atténuation		Oui	Non
17.	EPensez-vous qu'il est nécessaire que la qualité de		

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Table A.4 – continued from previous page

	l'air s'améliore dans votre entourage ?		
17.1	*Veuillez indiquer la raison de votre réponse (17)*		
18.	Pensez-vous pouvoir contribuer à l'amélioration de la qualité de l'air dans votre entourage ?		
19.	Faites-vous une activité (s) ou action (s) pour lutter contre la pollution de l'air ?		
20.	Voudriez-vous entreprendre une quelconque activité ou action p our lutter contre la pollution de l'air ?		
21.	Selon vous, lesquels de ces facteurs contribuent le plus à la pollution de l'air ? Veuillez encerclez les trois problèmes de la liste ci-dessous (1) Circulation routière (2) incinération des déchets (3) cuisine au bois ou au charbon de bois(4) travaux de construction (5) agriculture (6) poussière soulevée par le vent (7) émissions industrielles(8) fumée de cigarettes (9) utilisation des insecticides (10) utilisation de l'encens (11) autres		
22.	Selon vous, quelles et quelles actions l'état et/ou les municipalités doivent entreprendre pour lutter contre la pollution de l'air ?		

Continued on next page

Table A.4 – continued from previous page

	(Veuillez indiquer votre réponse .....

Table A.4: Questionnaire perception on air pollution

Toujours : Always, Fréquemment: Frequently, Parfois: Sometimes, Rarement: Rarely, Jamais: Never

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