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Source Apportionment of Air Particulates in South Africa: A Review

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Abstract

Source apportionment studies are useful in understanding sources of pollution and can be used in health risk assessments to evaluate the human health impacts from air pollutants. This study reviewed and analysed available source apportionment studies of air particulate in South Africa in October 2016. Searches were performed using different databases for peer reviewed articles including Google scholar, Scopus, EbscoHost, Science Direct and National Research Foundation database. Source categories were identified and these varied depending on the sites where the research was conducted (rural, urban or remote) but biomass burning dominated. A total of 35 source apportionment records were found with the majority of studies in urban areas (60%) while industrial sites had the least number of records (17.1%). The period 2011-2016 had the highest number of records while 1990-1995 had only three publicly available studies. There is limited research on source apportionment studies of air particulate in South Africa, calling for more research in this area.

Keywords

Air Particulate, Source Apportionment, Air Pollution, South Africa, Source Categories

1. Introduction

Research has revealed that world populations are now more exposed to ambient particulate matter than previously estimated [1] [2]. This is a major environmental issue mainly in highly industrialised and in some developing countries

[3] [4] [5]. The population in cities is at a higher exposure risk because of greater emission sources thus posing a higher health risk [6] [7] [8]. However, high emissions can also occur in rural areas and peri-urban areas due to domestic fuel use and particulates that are transported through long range transboundary means [1] [5] [9]. A strong relationship between airborne particulate matter and adverse health effects has been reported in literature [3] [10] [11]. Recently, [4] reported that 23% of all deaths and 24% of the global burden of disease can be attributed to environmental factors, especially ambient air pollution from particulate matter. Particulate matter contributes to 3.2 million deaths per year which translates to 3.1% of global total Disability-Adjusted Life Years (DALY) [4]. At global level, the increasing human population, urbanization and economic growth may exacerbate the impact on health.

Examples of the cited health issues include asthma, lung cancer and cardiovascular problems. Consequently, air quality standards have been set and enacted in the country so as to protect the public [2] [10]. The South African ambient air quality standards were revised and are now similar to standards in developed countries [12].

There is impetus to reduce exposure to air pollution or mitigate its effects on human health and environmental quality. Thus it is necessary to identify the sources and activities contributing to local air pollution levels. This is why studies on particulate matter source identification and apportionment of sources are needed. Source apportionment is a process of deriving information about pollution sources and the amount they contribute to the measured pollution concentrations. Various studies have identified sources of particulate matter responsible for air pollution in South Africa: mining [13] [14], vehicle emissions [15] [16], biomass burning [17] [18] [19], coal burning [1] and dust storms [1] [5] [9] [18] [19].

Research has shown that South Africa, which is the most industrialised economy in Africa, with a huge mining and metallurgical sector, produces the greatest industrial air pollution in Southern Africa region [20] [21]. Several South African studies have examined the link between soil or air particulates and human health [22] [23]. In South Africa, health problems resulting from airborne particulates have been reported in the Gauteng province which includes the large metropolitan areas of Johannesburg and Pretoria [2].

Different studies have used different source apportionment models and techniques that include source-receptor models, emission inventories, positive matrix factorization (PMF) and principal component analyses (PCA) which is a dimension reduction method [10] [24] [25] [26] [27]. Firstly, [28] investigated source apportionment of aerosols in the Kruger National Park using multivariate analysis. Secondly, were the applications of principal component analysis and modelling in which [29] investigated the source apportionment on aerosols, coal smoke and road dust in Soweto. Lately, [30] carried out a study on source apportionment using principal component analysis at different sites including Vaal Triangle, Amersfoort, Skukuza and Louis Trichardt. This study investigated ionic species such as NH_4^+, SO_4^{2-}, K^+, Cl^-, NO_3^-, Mg^{2+}, Na^+ and Ca^{2+}. Source receptor models and emission inventories have been applied in source apportionment of PM_{10}, SO_2 and NO_x in the Vaal Triangle [31]. In addition mass concentrations have been applied in several studies of source apportionment of air particulates in South Africa. These studies include [3] [32] who used mass concentrations on apportioning PM_1, $PM_{2.5}$ and PM_{10} in Rustenburg [5] [17] [33] [34] [35].

Recently, isotopic fingerprinting has been applied as another technique which is a key tool in source apportionment studies world-wide. The ratios of stable isotopes of a certain element, for example lead (Pb), can be used in identifying the origins of the element in that sample [36] [37] [38] [39] [40]. Isotope ratios are more sensitive tracers than elemental concentrations hence can be used as a reliable index to trace contamination and pollution sources in different environments such as air, soil and sediments. Studies on source apportionment using lead isotopic fingerprinting have been conducted in Switzerland [38], Australia [39], China [36] [37] [41] and South Africa [40] [42] where the focus was on aerosols in air, children's blood samples, street dust, lake sediments, reservoir sediments and lichens respectively.

Lead has four stable isotopes (^{208}Pb, ^{207}Pb, ^{206}Pb and ^{204}Pb) which are not measurably altered in chemical and biological processes after geological formation. This aspect makes it possible for lead isotopes to be used in apportioning contributions of major sources of pollution, especially where lead pollution resulted from multiple sources [36] [38]. However, only the first three isotopes of Pb (^{208}Pb, ^{207}Pb and ^{206}Pb) can be used in isotopic fingerprinting as ^{204}Pb is non-radiogenic and has almost a constant abundance value (~1.4%). ^{204}Pb therefore can be used as a reference isotope [37] [38].

Source apportionment studies are necessary to understand sources of pollution and implement health risk assessment. Source apportionment tools are valuable since they help in the design of effective emissions control programmes to reduce particulate air pollution [10]. Understanding the contributions of various emission sources is critical to appropriately manage the environment [12] [43]. This review quantifies the source apportionment studies done in South Africa with a focus on the main common methods used in source apportionment studies. The aim was to evaluate current trends in air particulate source apportionment studies and to identify possible gaps and future research directions.

2. Materials and Methods

Data Sources

Source apportionment studies in South Africa were searched using different databases for peer reviewed articles. These included Google Scholar, Scopus, EbscoHost, Science Direct, Sabinet and National Research Foundation database. The searches included the period 1990 to 2016 (October), a combination of key words with Boolean operators such as "AND/OR" commands. These words included source apportionment in South Africa, air pollution, air quality, $PM_{2.5}$, PM_{10} and ambient particulate matter. The time period was chosen because of unavailability of publications for the years 1989 and back. Unpublished data and results were not included in this study. It should be noted, however, that this review does not claim to be exhaustive of all source apportionment studies; it is an attempt to provide a comprehensive overview of air particulate source apportionment studies done in South Africa.

3. Results and Discussion

3.1. Source Categories

In South Africa, source categories differ depending on the sites where the research on source apportionment studies was done. For example Pretoria, which is an urban/industrial area, is likely to have source categories influenced by anthropogenic and industrial activities as well as mineral dust. However, Bloemfontein, which is a sub-urban and rural site with high vegetation, is influenced by smoke from biomass burning yet Cape Town, which is located in a remote coastal area, could be influenced by sea salt [11]. Contrary to this, some researches have shown that Cape Town's major source of pollutants is from vehicle emissions that contribute an approximate 65% of brown haze [44] [45]. The major source of brown haze in Cape Town is diesel vehicles contributing 48%, with petrol vehicles contributing 17%, followed by industrial boilers (13%) and wood burning (11%). Emissions from traffic are mainly associated with particulate air pollution in megacities such as Johannesburg and Pretoria.

Some studies have shown that the contributions of the various sources to the particulate matter such as biomass burning show seasonal variation for example [11] [18] [46] [47]. Biomass burning is identified as a major source contributor to PM during winter in some rural and township areas for example in Soweto [48] [49]. Ambient particulate concentrations can reach high levels which can be dangerous for the public and this mainly results from domestic fuel burning for heating purposes. The months August to October, being the dry season, are also associated with increased fire activity and this contributes significantly to particulate air [5] [20] [47] [50]. Notably, biomass burning is mainly concentrated in the tropical belt which accounts for more than 80% of the biomass burnt in the world of which half of it is during savannah fires [51].

Some studies have reported that the major source of particulate matter in Southern Africa is biomass burning [1] [11] [34] [46] [52] [53]. However, it has been noted that the importance of biomass burning as a contributor to aerosols has been overemphasized for South Africa and recent research has shown that south of 20˚S, aeolian dust is the major contributor to the total loading of aerosols in the lower troposphere over Southern Africa, followed by industrial sulphur [9]. This was supported by measurements taken from five remote sites in South Africa in which biomass burning contributed less than 5% to the total aerosol loading. These sites included Ben Macdhui in the Eastern Cape and Sutherland in the Karoo. Natural sources including dust and sea salt can be transported via long range transport. In the same way, residential coal combustion was the largest contributor of particulate matter to three sites in Qalabotjha with 62.1% $PM_{2.5}$ and 42.6% of PM_{10}. Biomass burning was the second largest contributor with 13.8% of $PM_{2.5}$ and 19.9% of PM_{10} [46].

Most of the biomass burning that significantly impacts upon South Africa comes from Zimbabwe and Mozambique [3] [17]. The emissions are also influenced by seasonal variation [5] [12] [21]. Recently, [3] reported highest concentrations of PM_{10} and $PM_{2.5}$ in winter in informal settlements and townships of South Africa and they attributed these to releases from domestic burning for cooking and heating. Similarly, [5] also concluded that the Bohlokong area is highly polluted in particulate matter, especially during winter times and the particulate matter concentrations exceeded the 24 hour USEPA standards.

Pollutants such as SOx and NOx and other secondary pollutants such as secondary ammonium sulphate are dominant in areas which have many industries such as Mpumalanga Highveld areas and these usually do not show any seasonal variation [44] [50] [54]. [54] stated that of the 1.1 Mt of sulphur emitted into the southern African region annually, 66% is from South Africa of which 90% is from the Mpumalanga Highveld area. Furthermore, [55] showed that major source contributions in the Vaal Triangle region emanated from soil dust, domestic coal combustion, secondary ammonium sulphate, iron arc furnaces and power station fly ash. **Table 1** shows the major source categories identified in the studies.

3.2. Available Researches on Source Apportionment in South Africa

Several air quality monitoring stations have been installed in urban and rural areas across South Africa. As presented by [56], there were 17 air pollution monitoring networks in South Africa in 2014 of which 14 were government owned and three were industry owned. The total number of monitoring stations was 101 with data available back to 2004 [56]. However, the main interest of these stations is on specific species and their trends over a period of time rather than source apportionment. For instance the chemical species investigated and their trends over time include ozone (O_3), sulphur dioxide (SO_2), carbon monoxide (CO), ammonia (NH_3), nitrogen dioxide (NO_2) and other pollutants. For example, the Aerosol Recirculation and Rainfall Experiment (ARREX) experiment during 1997-1998, Southern African Fire-Atmosphere Research Initiative (SAFARI) conducted in 1992 and Southern African Regional Science Initiative (SAFARI) in 2000 [9] [57]. The Deposition of Biogeo-chemically Important Trace Species (DEBITS) project also installed air monitoring equipment at several sites in South Africa. These include Louis Trichardt (rural site) and Amersfoort (industrially influenced site). The Cape-Point Trace Gas Research Station measures air pollutants (CO, CO_2, CH_4, N_2O, O_3 and CFC) and meteorological

Table 1. Major source categories identified in the studies.

Site	Source categories
Urban	Anthropogenic (e.g. vehicle emissions) and industrial emissions
Sub-urban and rural	Biomass burning (e.g. domestic coal burning), vehicle emissions, industrial emissions.
Industrial	Industrial emissions, vehicle emissions, soil dust
Remote coastal areas	Sea salt, vehicle emissions, soil dust, biomass burning

parameters such as wind speed, wind direction, atmospheric temperature and pressure on a long term basis. Recently, Welgegund station located approximately 100 km west of Johannesburg was established for atmospheric measurements as well as capturing regional background concentrations and emissions from major source regions in the interior of South Africa. These include Johannesburg-Pretoria area, industrialised western and eastern Bushveld Igneous Complex, Vaal Triangle and the industrialised Mpumalanga Highveld [20].

It was noted that sources of NO_2 and SO_2 were mainly from industrial pollution in the Mpumalanga highveld area and the more distant sites from the coal-fired power plants and mine (sources) had the lowest concentrations [33]. Recently, it has been highlighted that the Mpumalanga Highveld area (most industrialised region in South Africa) accounts for 90% of NOx and other gas emissions in South Africa [44]. However, the perception from the public that industries are the major source of air pollution was not confirmed in several studies carried out by different scientists. For example, motor vehicle emissions contributed significantly to air pollution in urban areas through release of NOx gases [35]. Studies on air particulate source apportionment conducted in South Africa between 1990 and October 2016 reveal that most studies (56.5%) have been done on aerosols while $PM_{2.5}$, PM_{10} and NOx account for 30.4% of the total studies. The least number of studies reviewed for the period were on PM_1, trace metals and carbon monoxide and these account for 13.1%. However in Europe the studied PM mass fractions by source apportionment using receptor models were in the order PM_{10} (56%) followed by $PM_{2.5}$ (37%) and PM_1 (6%) [58].

3.3. Methods Used in Source Apportionment of Air Particulates

It was observed that the studies from different authors looked at 23 species altogether. These species include PM_{10}, $PM_{2.5}$, PM_1, SO_2, NO_x, O_3, CO, trace metals and others. Considering the methods used in source apportionment studies, the most common method used was trajectory analysis which had 12 studies, followed by using mass concentrations which had ten studies of apportioning air particulate species to their sources. Mass concentration refers to the ratio of the mass of the chemical species to the volume occupied.

For example, during measurements of air particulates, different size channels are grouped into four categories PM_{20}, PM_{10}, $PM_{2.5}$ and PM_1. To achieve mass concentration, an average aerosol density if 1500 kg/m^3 was used [5]. Furthermore, principal component analysis and aerosol optical characteristics which include aerosol optical depth, scattering, and absorption had four studies each. Additionally, chemical mass balance model was not very popular as it used in two studies. Finally, methods such as using tracer elements in which specific elements or species were used to identify certain source categories, Positive Matrix Factorization and multivariate analysis had the least with just one study using each technique for source apportionment (**Figure 1**). However a study could combine different methods for source apportionment so as to get more robust results.

3.4. Sites Where Source Apportionment of Air Particulates Were Reviewed

This review shows that most of the work on air particulate source apportionment studies was conducted in urban areas (60%), followed by rural areas (22.9%) and lastly industrial areas (17.1%). The present findings are consistent with other research for example at a global level which found that 77% of the source apportionment studies were in urban areas followed by rural (14%), remote (5%) and industrial areas (4%) [1]. Similarly in Europe source apportionment studies in urban background areas constituted 67% whereas 13% were conducted in rural background sites [58]. **Table 2** shows the number of available studies which are also expressed as a percentage for the study period.

Some regions of the world such as Africa have no or very few data on ambient particulate matter source apportionment studies [1]. [1] noted that for the period 1990 to August 2014, Africa had a total of 11 studies in urban areas, four on $PM_{2.5}$ and seven on PM_{10} of which South Africa had only two records. These findings confirm that there is poor documentation on source apportionment

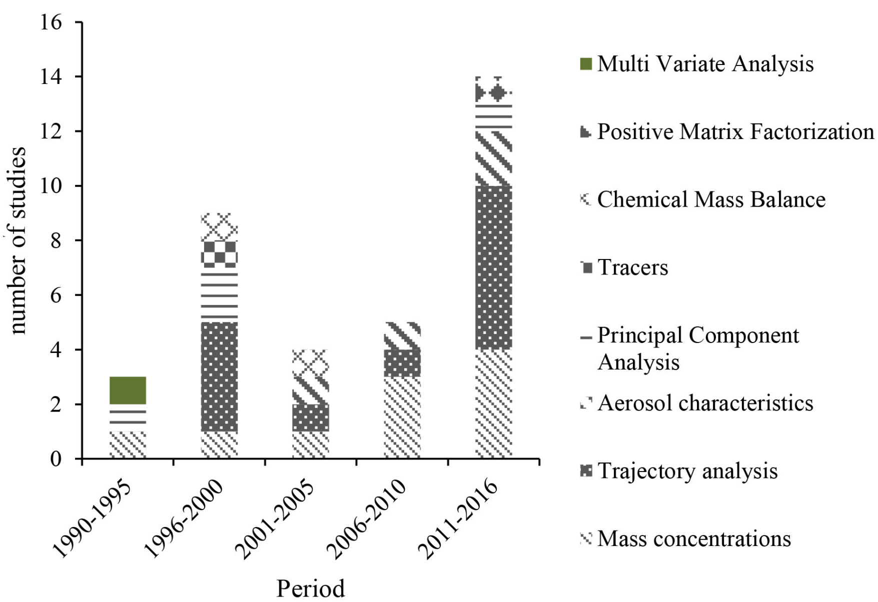

Figure 1. Methods and techniques used for source apportionment studies.

Table 2. Percentage of studies in different areas from 1990-October 2016.

Site	Number and Percentage of studies
Urban	21 (60%)
Rural	8 (22.9%)
Industrial	6 (17.1%)

NB Classification of the study area was based on information from the publication on description of study area.

studies of ambient air and information available is scarce not only in South Africa but in Africa as a whole. This evidence is further supported by [59] who observed that pertaining to air quality, Africa is one of the least studied continents in the world.

It can be noted that most source apportionment studies on air particulates in South Africa recorded were for the period 2011-October 2016 when this review was conducted followed by the period 1996-2000 (**Figure 2**). However, for the period 1990-1995, only three studies were publicly available. Thereafter, the period 2001-2005 recorded a slight increase in the records. The period 2006-2010 also had an increase of two publications compared to 1990-1995 which had the lowest number of publications. It was difficult to find possible reasons for the decline in publications from nine in 1996-2000 to four in 2001-2005 and five in 2006-2010 but the peak afterwards (2011-2016) with 14 publications showed an improvement in the research work. The reason for this was not clear but suggestions include improved funding of research in the area of air quality studies and increased concern of particulate matter adverse health impacts as well as the association with regional climate change. **Figure 3** shows the trends of available studies in published literature on source apportionment studies in South Africa for the period 1990-2016.

4. Conclusions

Source apportionment studies are useful to policy makers as these help in policymakers understanding air pollution that enables them to work out remedial strategies for its abatement. For reducing health effects of air pollution, it is important to know the sources contributing to human exposure. Only 35 studies are publicly available for the period 1990 to October 2016. This study noted that source categories do not vary a lot in the individual studies reviewed where basically the major sources identified for the air particulates are biomass burning, coal burning for domestic fuel use and industries and motor vehicle emissions. Species which were investigated by the authors in the source apportionment studies of air particulates include aerosols, PM_{10}, $PM_{2.5}$, NOx, trace metals, ozone, SO_2, CO and NH_4^+. Most of the work on air particulate source apportionment studies was conducted in urban areas followed by rural areas and lastly in industrial areas. Most source apportionment studies on air particulates in South Africa were for the period 2011-October 2016, the time when this review was done.

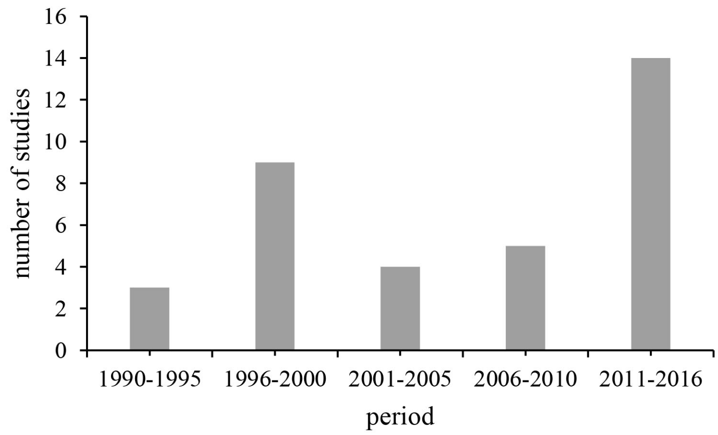

Figure 2. Summary of the available studies published in literature for the period 1990-October 2016.

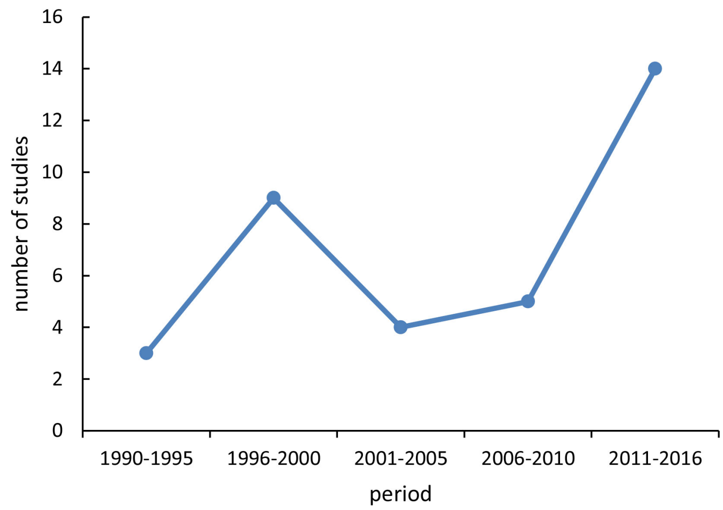

Figure 3. Trendline showing the available studies published in literature for the period 1990-October 2016.

However, the period 1990-1995 had only three publications which were publicly available.

Based on the results of this review, it is suggested that the following points should be taken into consideration when designing future research work: 1) more research into air particulate source apportionment techniques and tools in the different provinces in South Africa as the available information is scarce and poorly documented, 2) comparisons between source apportionment methodologies is particularly important due to some uncertainties that are inherent in some methods.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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