Particulate air pollution in Indonesia: quality index, characteristic, and source identification

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Abstract. The growth of urbanization, industrialization, and economic development in many areas in Indonesia contributes to the rise of particulate matter (PM) in the atmosphere. PM is strongly correlated with the severe air pollution that can lead to several health problems and early mortality. Other than continuous concentration monitoring, a good understanding of chemical characteristics and sources of PM is important for effective management and mitigation of air pollution. The aim of this study was to summarize the spatial distribution of the PM (PM$_{2.5}$ and PM$_{10}$) concentration level, chemical characteristics, and sources apportionment in several cities in Indonesia based on systematic Scopus and Google searches for the period of publication year between 2008 to 2019. The studies of 10 cities showed most of the cities' PM$_{2.5}$ and PM$_{10}$ average concentration have exceeded the annual average standard of both Indonesian regulation and WHO standards. Generally, traffic emissions were the majority sources, followed by biomass burning and dust emission. Forest and peat fires did contribute to high biomass burning emission in the downwind cities. The findings help to give the image of the status and the nature of particulate air pollution problems in Indonesia. Current issues and future research needs were also discussed.

1. Introduction
As a developing country, urbanization and development regarding economic expansion become more prominent in Indonesia. More than 50% of the total Indonesia’s population now occupied the urban area. The growth rate of Indonesia urban population is one of the highest in Asia [1]. In the transportation sector, based on the Central Bureau of Statistics Republic of Indonesia, the total number of motor vehicles in Indonesia per 2018 was 146.8 million units with the growth rate average is 8.3% for the last ten years [2]. All of these anthropogenic activities can contribute to more particulate matter in the atmosphere. Particulate matter (PM) are tiny particles found in the air which is formed in the atmosphere because of chemical reactions between pollutants. Based on the main size, PM divided into two main groups: PM$_{2.5}$ and PM$_{10}$. PM$_{2.5}$ means particulate matter with aerodynamic diameter less than 2.5 µm (fine PM), while PM$_{10}$ represents particulate matter with aerodynamic diameter between 2.5 - 10 µm (coarse PM).

The rise of PM presence in the atmosphere become concerned because it is strongly correlated with severe air pollution and health problems. PM is currently considered to be the essential human health indicator in ambient air pollution [3]. PM$_{10}$ have long been studied can causing adverse effect and increasing mortality, whereas PM$_{2.5}$ impose even higher risk [4]. In addition for regular anthropogenic activities, forest and peat fires originating from Kalimantan and Sumatra have become an annual
phenomenon that occurred almost every dry season in Indonesia, worsening the condition of PM pollution. This phenomenon not only causing local pollution but also transboundary haze pollution. A study reported the association between the forest and peat fires with early mortality in Indonesia [5].

Other than availability and accessibility of air quality monitoring systems, one of the important things for air quality management is to identify the contributions of different source sectors and regions to air pollutants. Air quality modeling helps to provide the causal link between emission and ambient concentration of air pollutants. A clear understanding of the primary sources is the first important step for establishing strategies for air pollution control [3]. A systematic review of PM sources in Indonesia is a great help for a better understanding of spatial diversity of air pollution in Indonesia and for policymakers to develop effective air pollution control measures in the specific area in Indonesia. This review aims to assess the air particulate emission and its related monitoring system, the chemical characteristic and source apportionment studies in Indonesia by synthesizing results from published literature. Furthermore, the challenge as well as the prospect of PM studies in Indonesia were discussed. The data sources were originally from systematical searched of Scopus database and World Wide Web using Google search with the combination of the following keywords: source apportionment, particulate matter, PM$_{2.5}$, PM$_{10}$, air pollution, atmospheric aerosol, Indonesia. The research included the period of publication year between 2008 to 2019. The analysis in this study comprises of three steps: (1) identifying data sources (2) extracting data, and (3) summarizing the particulate matter studies.

2. Air Particulate Pollution in Indonesia

2.1 Pollution level, chemical characteristic and sources profiles of particulate matter in Indonesia

Air quality standard is one of the essential aspects of an air quality monitoring network. In Indonesia, the standard is managed in Indonesian Government Regulation No. 41 of 1999. Other regulations that also commonly used worldwide are regulation by WHO and US EPA. As for in ASEAN countries, the standard by US EPA usually referred to. Table 1 depicts the summary of the ambient particulate matter quality standard. Among all standards, WHO guidelines set the lower number; thus, many countries have difficulty satisfying this standard.

| Standard                                | PM$_{2.5}$ (µg/m$^3$) | PM$_{10}$ (µg/m$^3$) |
|-----------------------------------------|------------------------|----------------------|
| Indonesian Government Regulation No 41 of 1999 | 65     | 15     | 150 | -     |
| USEPA                                   | 35     | 15     | 150 | 50    |
| WHO                                     | 25     | 10     | 50  | 20    |

In this study, database of PM studies from several cities in Indonesia were collected and analyzed. The studies measured PM mass concentration for comparison data, characterization, and further source identification. Table 2 summarizes PM studies in 11 cities in Indonesia. The table contains sampling site location types, sampling period, PM average concentration, used method, and the major source of PM with its chemical signature.

The average of PM$_{2.5}$ concentration in the mentioned cities are in the range of 11.88-140 µg/m$^3$. Assuming that all the studies can represent the annual mean, most of the cities have surpassed the annual limit standard of Indonesia regulation with 15 µg/m$^3$, whereas referred to WHO standard, all the cities had over the WHO standards. Though the study in Pekanbaru has a particular condition that was performed during peat forest fires episode, it is then become an important note that the peat fires gave a significant contribution to the downwind cities located 220 km from the peat fires location. The high contribution of the peat fires made the PM$_{2.5}$ concentration far higher than any standard limit of 194 µg/m$^3$. One of the challenges of air pollution management in Indonesia is the absence of PM$_{2.5}$ in Indonesian air quality index (ISPU) monitoring, although PM$_{2.5}$ is an important parameter that strongly relates to human health.
Table 2. Particulate matter studies in several cities in Indonesia

| City          | Location type | Sampling period | PM size fraction | Average concentration (µg/m³) | Method | Major source                  | Signature component | Ref |
|---------------|---------------|-----------------|------------------|------------------------------|--------|------------------------------|---------------------|-----|
| Pekanbaru     | Urban         | Mar 2005\*      | PM₁₀₂₅          | 140                          | CMB    | soil dust                    | Al, Fe, Ti          | [6] |
|               | Urban         | Sept 2015 - Mar 2016\* | PM₁₀₂₅         | 94.41                        | CMB    | forest fires                 | K, SO₄²⁻, NO₃⁻      | [7] |
|               | Urban         | Sept 2015 - Jan 2016\* | PM₁₀₂₅         | 192.1                         | PMF    | biomass burning              | SO₄²⁻, K⁺           | [8] |
| Cilegon       | Industrial    | Aug-Nov 2015    | TSP              | 187.35                        | PMF    | crustal matter               | Al, Si, Ti          | [9] |
| Serpong       | Industrial    | Aug-Nov 2008    | PM₁₂₅           | 22.1                          | PMF    | diesel vehicle               | S, Pb, Zn           | [10]|
|               | Urban mixed   | 2011-2013       | PM₁₂₅           | 14.07                         | PMF    | transportation               | S, Mn, K, Ca, BC    | [11]|
| Jakarta       | Urban         | 2008-2009       | PM₁₂₅           | 25.76                         | PMF    | motor vehicles               | S, BC               | [12]|
| Lembang       | Suburban      | 2002-2004       | PM₁₂₅           | 11.88                         | PMF    | soil and road dust           | Al, Si, Ca, Fe     | [13]|
|               | Urban mixed   | 2001-2007 (dry season) | PM₂₅₃          | 48                            | PMF    | secondary aerosol            | NH₄⁺, SO₄²⁻, NO₃⁻   | [14]|
|               | Urban mixed   | 2001-2007 (wet season) | PM₁₀₂₅         | 19                            | PMF    | diesel vehicle               | BC, SO₄²⁻, Fe, Zn   |       |
|               | Urban         | 2002-2004       | PM₁₂₅           | 14.03                         | PMF    | sulphate-rich industry       | Al, S, Cr, Cl      | [14]|
|               | Urban         | 2002-2004       | PM₁₀₂₅          | 17.64                         | PMF    | N/A                          | N/A                 | [13]|
| Jepara        | Suburban      | Mar-Jun 2018    | PM₁₀₂₅          | 181.75                        | PMF    | transportation               | Sb, Zn              | [15]|
| Semarang      | Urban mixed   | May-Jun 2005    | PM₁₀₂₅          | 74.74                         | CMB    | transportation               | Mn, Al, Ca, SO₄²⁻   | [16]|
| Probolinggo   | Industrial    | Jul-Aug 2018    | PM₁₀₂₅          | 150.35                        | PMF    | biomass burning              | K, Mg, Mn, Al      | [17]|
| Surabaya      | Urban         | 2012-2014       | PM₁₀₂₅          | 15.05                         | PMF    | vehicle                      | S, BC               | [18]|
| Makassar      | Urban         | 2012-2013       | PM₁₀₂₅          | 32.9                          | Enrichment factor | marine or anthropogenic sources | SO₄²⁻, NO₃⁻, Cl⁻ | [19]|

\*including fires episode

In the case of PM₁₀, the average concentration is in the range of 7.1-192.1 µg/m³. The annual average concentration for PM₁₀ is not available in the national regulation, with daily average concentration of 150 µg/m³, while US UPA and WHO standard are one per three lower than Indonesian regulation standard. There are two cases where the national daily average standard limit was surpassed. Those are in Pekanbaru with an average concentration of 192.1 µg/m³ and Jepara with 181.75 µg/m³. A study in Pekanbaru was conducted during pet fires episodes within two months of monitoring. Thus, the PM₁₀ concentration rose high in the category of moderate level based on Indonesian air quality index (ISPU), while referring to the US EPA air quality index that value matches with unhealthy category [8]. Pekanbaru is an urban area with a population of more than 800,000 people, and the occurrence of peat fires exposes the detrimental effect to this downwind city. The sampling site at Jepara was in densely populated areas with poor waste management, thus the study mentioned that this condition resulted in high biomass burning activities [15]. This should be a warning to urge actions for better waste management and the prohibition of solid waste
burning. PM$_{10}$ levels in most of the cities have been surpassed the annual WHO standard. TSP and SPM were considered less relevant from the health standpoint. Therefore, monitoring and study of PM$_{2.5}$ and PM$_{10}$ are more encouraged.

Other than continuous monitoring of PM, the study of chemical composition and source identification are essential to evaluate the health impact of PM and to mitigate the potential sources. The understanding of PM source contribution is a necessary step for analyzing the potential effects of natural and anthropogenic sources on human health. Source apportionment (SA) is the modeling technique used to relate the emissions from pollutions sources to the concentrations of such pollutants in ambient air. SA techniques commonly used are receptor models or source-oriented models. Receptor models are based on the measured concentrations of pollutants and their components, while source-oriented models are based on transport, chemistry, and dispersion models [20]. Positive Matrix Factorization (PMF) and CMB (Chemical Mass Balance) are the most widely used source apportionment methods in Indonesia. The ideal data source for PMF required fairly large datasets with reasonable uncertainties, while CMB is applicable with small dataset available. However, CMB model model is not able to separate the sources having similar chemical compositions or for the sources in which the source composition profiles are unavailable [21].

Chemical composition characterization is the base to identify the source profile for PM source apportionment study. PM source profile means mass fraction of chemical component to particulate matter from a specific primary source [22]. PM consists of organic and inorganic compounds that are released from primary pollutants or are formed by secondary reactions. Primary pollutants are directly released into the atmosphere, while secondary pollutants (such as ozone and secondary PM) are formed in the atmosphere through chemical reactions of gas precursors [23]. Chemical components act as source signature in the receptor modeling of source apportionment. Through different sampling methods and instruments, the element being analyzed for chemical speciation study and further for source apportionment identification include but not limited to carbonaceous aerosol, metal element, and inorganic secondary ions.

80% of the compiled source apportionment studies mentioned on the table above were done using PMF technique. Most of the studies used metal element as the element signature for the source contribution identification. Elemental measurements are necessary but insufficient for a receptor modeling study alone. Other chemical speciation must also be included. The organic compound analysis would be a big help for source characterization. However, these analyses are more difficult or costly to apply than currently available elemental, ion, and carbon measurement [24]. SPECIATE source profile database was mostly used for the reference of source profiles. SPECIATE is a US comprehensive source profiles database. Indonesia itself has not yet has source profile database.

2.2 Particulate matter source apportionment in Indonesia
In this section, source contribution using receptor models in Indonesia based on the study in 10 cities were summarized. Makassar was not included due insufficient source apportionment data. The studies summarized in spatial distribution are the latest studies that including article papers both in English and Bahasa. Figure 1 displays the graphical summary of PM source contribution over several cities in Indonesia.
Figure 1. Particulate matter source apportionment in Indonesia. The reference of each city are as follows, Pekanbaru [8], Lembang [13], Bandung [14], Surabaya [18], Probolinggo [17], Jepara [15], Semarang [16], Jakarta [12], Serpong [11], Cilegon [9]. Note: “others” categories in Lembang means other sources that are not mentioned by the author since only the major contributor is mentioned. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this article).

From the averages of source contributions, 19% of particulate matter was contributed by vehicular sources, 18% biomass burning activities, 16% each for dust and industrial sources, 14% for coal combustion, 13% of secondary aerosol and 4% are from other sources. A similar result from a previous study stated that the transportation sector contributed 83% of the concentration of the fine particles in Jakarta [25]. Some other studies at the global level and another place were also found out the primary sources of the air pollution problem are mainly from the transportation sector. A study of local source contribution at a global level found out 25% of urban ambient PM$_{2.5}$ was contributed by traffic emission [3]. The spatial distribution study of fine particulate matter in China revealed that secondary sources and traffic emission are the major contributors [22]. The second large contributor in Indonesia's particulate pollution is biomass burning activities. The term biomass burning referred to several types of activities, including the burning of the forest, peat, crop residue, and municipal solid waste. Forest and peat fires frequently occurred during dry season in Indonesia that caused negative impact on the atmospheric environment not only in the local area but also in surrounding countries. Crop residue burning can be found quite often in the rice field, moreover municipal solid waste burning also still often occurred in a crowded area and exposing air quality deterioration and adverse human health effects. A previous study in 1996 reported that biomass burning was a major source representing 44% of fine fraction mass in Indonesia [25]. Nevertheless, it is important to be noted that this summary result is from different studies with different particulate size fractions, analytical methods, and ambient sampling condition in different periods, which possibly produce bias to the spatial source pattern. This study intends to give a general image of PM source patterns over several cities in Indonesia.

3. Challenges and future development
Air quality management in Indonesia essentially needs more improvement for better environmental protection. In the monitoring aspect, the current condition mostly focuses on total suspended particle (TSP) or PM$_{10}$ concentration. Considering the higher risk imposed by PM$_{2.5}$, the air quality monitoring system should add more PM$_{2.5}$ as the primary parameter.
Refer to the trend of PM concentration of the cases summarized in this study, current standards in the related national regulation are important to be evaluated. In addition, the implementation of Euro 4 strategy should be applied immediately, considering the high contribution from the transportation sources for PM air pollution.

PM source apportionment research area in Indonesia is still wide open for more development. The number of comprehensive source apportionment studies that can represent well the city condition is still limited. The wide diversity of sampling periods, the number of sites, uncertainties of sampling and chemical analysis, and choices of source markers resulting in a wide difference in the available results of source apportionment studies. The difficulty and the high cost to perform the research could become the reason for the limited available studies in particulate matter source apportionment. This condition makes it is not easy to make a proper comparison. Some of the possible ways to evaluate the source apportionment results are the importance of basic knowledge on the city background area before conducting the research due to different regions have different geographical, meteorological, and emission categories. A better understanding of local area-specific emission inventories for specific chemical components is needed so that it can be a great help in the utilization of multivariate receptor models in the future.

To improve the robustness of the source apportionment study, the combination of multiple receptor models can be a good addition. Further analysis after source apportionment, such as back trajectory analysis, will be helpful to distinguish the local and regional sources [22]. The opportunity for future research is the application of source-oriented models, which is still rarely used. The availability of emission inventory is essential for the implementation of source-oriented models. Source oriented model is advantageous in simulating and forecasting air quality in different spatial and temporal scales. However, in the meantime, the improvement of receptor models is a good option for the study of particulate matter with accurate physical and chemical information.

4. Conclusion
This study summarizes the particulate matter source apportionment studies in Indonesia in order to give the image of the current state of level with its related monitoring system and regulation, as well as the nature of particulate air pollution problems in Indonesia. The findings of this study found that the PM concentrations both in the form of fine and coarse across Indonesia mostly have surpassed the standard limit of annual national regulation and WHO standards. During the fire episode days, PM concentration rose significantly violate the national standard limit in the surrounding downwind cities. Most of the studies used metal element as the element signature for the source contribution identification. This study suggests traffic and biomass burning are important contributors to particulate matter emission in several locations in Indonesia. Implementing the related regulation and prioritizing the healthy transport system are encouraged as a promising solution. This review emphasizes the need for further attention to assessing PM pollution, especially for fine particles due to its high health impacts. Moreover, the needs of evaluation through national standard limit for PM concentration along with the national standard for air pollution index. Future research should address the evaluation source apportionment techniques used, establishment of local source profiles, and the application of source-oriented models. Finally, this study urges the importance of building a comprehensive air quality information system for publishing and sharing of monitoring data across governmental, academic, and other institutions. This integration would greatly facilitate the identification of PM problems, as well as the planning and implementation of future studies.

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