Application of nuclear analytical techniques to assess air quality in Indonesia

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Abstract. Air pollution has become a global concern because of its effects on the environment and human health. Nuclear analytical techniques (NATs) have important application in air pollution monitoring and research. NATs such as Instrumental neutron activation analysis (INAA), Particle Induced X-ray Emission (PIXE), X-ray fluorescence (XRF), and X-ray absorption near-edge structure (XANES) have been used in quantification of environmental pollutant especially airborne particulate samples (APM) collected from several cities in Indonesia. The samples were analysed for elemental concentrations by INAA at Siwabessy multipurpose reactor and Bandung TRIGA 2000 reactor in Indonesia, PIXE at Institute of Geological and Nuclear Sciences New Zealand, XRF at BATAN Bandung Indonesia, and Synchrotron facilities at Elettra Italy. The techniques provide more than 20 significant elements for identification the possible sources of atmospheric aerosol. The results demonstrated that INAA, PIXE, XRF and XANES can complement significantly the elemental characterization of APM providing the concentration of several major, minor and trace elements. These results can be used as important information on levels and sources of air pollution. It could also be used as an early warning, scientific research-based references in designing and revising various government policies and regulations related air quality standards in Indonesia.

1. Introduction
Rapid urbanization and industrialization have created severe air pollution problems, particularly in major urban cities in Indonesia. Air pollution has become a significant health threat to urban residents and caused a loss of productivity in the nation. There are many factors that cause air pollution, but the most significant factors are population growth and rapid urbanization. Since urban areas offer more opportunities for a better quality of life, education, employment, so it is expected that the majority of Indonesians will live in urban areas. This urbanization has also increased demand for transportation, which in turn means increased air pollution. Therefore there is a strong need to keep the quality of the environment at acceptable levels [1].

Epidemiological study showed that there is a significant relationship between levels of airborne particulate matter (APM) levels with mortality and morbidity. Health effects of APM depend on the concentrations and size of particle. Particles in the size range of about 10 um and 2.5 um (PM\textsubscript{10} and PM\textsubscript{2.5}) are very dangerous since this size can penetrate into the airways where they may exert adverse effects [2], [3]. Because of many adverse effect’s particles in large number of people caused by APM especially fine particles, therefore PM\textsubscript{2.5} become one of the main pollutants that must be monitored closely.
Air pollution monitoring in Indonesia, in general, is still focused on total suspended particulate (TSP) or PM$_{10}$ (particles with aerodynamic diameters less than 10 um). The published data on PM$_{2.5}$ concentrations and chemical compositions of APM is still scarce and limited. These data are needed to determine the possible sources. For appropriate air quality management, the source of particles air pollution must be known qualitatively. For this reason, the nuclear analytical techniques (NATs) such as instrumental neutron activation analysis (INAA), particle induced X-ray emission (PIXE), X-ray fluorescence (XRF), and X-ray absorption near-edge structure (XANES) is used to characterize the filter samples of APM. Nuclear techniques have been applied to the characterization of particulate matter from air pollution in around the world [4], [5], [6], [7], [8]. Their simultaneous measurement, multi-elemental capabilities, high sensitivity, short analysis time and nondestructive properties make them ideal for this type of work. Depending on the quality of the air at the sampling location, airborne particulate samples collected in the filter may only contain a very small sample mass, sometimes less than 100 micrograms, making it difficult to analyze with conventional methods. Furthermore, the large numbers of samples obtained from air quality monitoring can be more efficient if the sample analysis in carried out using multi elemental techniques such as NATs. This technique can produce large data sets that can be used to characterize pollution sources as well as estimating different source contributions that are very important for understanding air pollution and air quality management. Therefore, the characterization of airborne particulate matter become important. This paper discussed the application of INAA, PIXE, XRF and XANES in characterization the airborne particulate matter in Indonesia. Discussion on the use of NATs for multielemental characterization will be focused on particles with an aerodynamic diameter of less than 2.5 µm.

2. Materials and methods

2.1. Sampling and sample preparation
Airborne particulate matter was collected from several sites in Indonesia using a dichotomous Gent stacked filter unit sampler. Samples of fine particulate (PM$_{2.5}$) and coarse particulate (PM$_{2.5-10}$) were collected at least once a week for 24 hours at a flow rate of 15-18 L/min, stored in clean room at the relative humidity below 60% and temperature of 18 – 25°C for mass stabilization [9]. The particulate masses of each PM$_{2.5}$ and PM$_{2.5-10}$ are determined by gravimetric. Particulate mass of each samples was determined by weighing the filters before and after exposure using a microbalance. The difference in weights for each filter was calculated and mass concentrations were obtained by dividing the gravimetric mass by the volume of air that passed through the filter to obtain the concentration of PM$_{2.5}$ and PM$_{2.5-10}$. While, PM$_{10}$ concentrations can be obtained from the sum of PM$_{2.5}$ and PM$_{2.5-10}$ concentrations. For the concentration of black carbon (BC) in the samples was determined by reflectance measurement using an EEL model 43D Smoke Stain Reflectometer. This method is based on the absorption is proportional to the black carbon concentration on the filter. The black carbon concentration values were obtained according to the method described by other researchers [10].

2.2. Elemental analysis.
The elemental analysis using INAA Bandung TRIGA 2000 and XRF were carried out at BATAN Bandung which has implemented ISO/IEC 17025:2005 and accredited by National Accreditation Body. INAA was also conducted at Siwabessy Multipurpose Reactor in Serpong Indonesia. Analysis using PIXE was carried out at the Institute of Geological and Nuclear Sciences (GNS) New Zealand, while XANES in Elettra Italy. The samples collected in 2004 were analysed for elemental concentration by INAA. The irradiation procedure and the counting have been written elsewhere [11]. Elemental analysis of samples collected in 2005 to 2010 was performed using PIXE at GNS New Zealand. For the samples collected during 2011 to 2016 were analyzed by XRF, while selected samples collected in Surabaya were analyse by XANES.

The Instrumental Neutron Activation Analysis with relative method was carried out for elemental analysis of the samples. Neutron Activation Analysis (NAA) is a sensitive analytical technique which useful for performing both qualitative and quantitative multi-element analysis of major, minor, and trace elements in samples from almost every field of scientific or technical interest. It is one of the
most mature analytical methods currently used and yet remains highly compete with others in term of accuracy, detection limits and multi elemental capabilities. The samples placed in the 0.3 mL polyethylene vials. SRM NIST 1648 airborne particulate used to validate the method was weighed about 25 mg and placed in the 0.3 mL polyethylene vials. Mix standards for relative method were prepared and placed in the same size vials. The samples, SRM and standards are ready for irradiation. The samples, SRMs and standards were irradiated in the rabbit system of the Multi-Purpose Reactor G. A Siwabessy and lazy Susan irradiation facility at the Bandung TRIGA 2000 reactor with thermal neutron flux \( \sim 10^{13} \text{n.cm}^{-2}.\text{s}^{-1} \). Short, medium and long irradiations were performed in order to determine various radionuclides with different half-lives. After appropriate cooling, samples were counted for about 5 minutes for short-lived radionuclide, and within 30 to 60 minutes for medium and long-lived radionuclides using HPGe gamma spectrometer. Software GENIE 2000 was utilized for spectrum analysis [8], [11], [12].

The XRF analysis was conducted using Epsilon 5 EDXRF spectrometer from Panalytical, which has a 100kV excitation source and a polarising optical path give detection limits in the low ng/cm\(^2\) range for most elements. EDXRF Epsilon 5 with its polarization method produces an indirect exitation/secondary target excitation gives significantly lower background. A special sample insert enables air filters to be fitted directly into the sample cup. No additional sample preparation is needed and the sample changer makes continuous analysis possible. The EDXRF Epsilon 5 installed in BATAN Bandung has 9 secondary targets i.e: Al\(_2\)O\(_3\), Fe, CaF\(_2\), Ge, Zr, CeO\(_2\), Mo, Ag and Al. The calibration was set up using a multi standard reference material, standard Micromatter® and a blank standard for each elements, Mg, Al, Si, S, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As and Pb. The validation of XRF measurements in this application was applied using standard reference material SRM NIST 2783 Air Particulate on Filter Media [13].

The PIXE analysis was performed at the National Isotop Center, GNS Science New Zealand. The X-ray spectra were analysed using the computer code GUPIX. Calibration of the PIXE system was performed by irradiating the suitable Micro Matter thin target standards [14]. Concentration of the elements were measured and analyzed for the fine and coarse filter samples.

X-Ray absorption near edge structure spectroscopy (XANES) was used to determine the oxidation states and modes of occurrence of selected element in filter samples [15]. The selected APM sample collected from industrial area in Surabaya was then analyzed using XANES for Zn speciation with 15s/step and 20s/step respectively. The measurement was continued for analyzing several standards foil with 1s/step. XRF scanning was then applied for SRM NIST 2783 blank filter and APM using the similar procedures with energy of 13.5 keV, 100s/step. The selection of Zn element for XANES analysis was due to the higher Zn concentration in Surabaya, which was significantly different compared to other cities [13], [16].

### 3. Result and discussion

The characterization of fine and coarse particulates has been carried out by BATAN since early 2000 by conducting sampling in 2 locations namely Bandung as urban and Lembang as rural. The average concentration of fine and coarse particulate in the period 2002-2004 showed the mass concentration of PM\(_{2.5}\), PM\(_{10}\) in Bandung and Lembang were 14.03, 11.88 and 31.67, 18.98 \(\mu\text{g/m}^3\), respectively [17]. These results still did not exceed the Indonesia’ National Ambient Air Quality Standard (15 and 150 \(\mu\text{g/m}^3\)) for both PM\(_{2.5}\) and PM\(_{10}\).

After 10 years later, mass concentration of PM\(_{2.5}\) and PM\(_{10}\) in Bandung during the period 2012 - 2013 shown in Figure 1. It can be seen that the averages of PM\(_{2.5}\) mass in Bandung during this periods was 15.56 \(\mu\text{g/m}^3\), slightly higher than the annual average of national standard (15 \(\mu\text{g/m}^3\)). This needs attention because PM\(_{2.5}\) is one of the parameters of air pollution that has a significant impact on human health. While, the average of PM\(_{10}\) concentration was 41.06 \(\mu\text{g/m}^3\) with a maximum value of 66.23 \(\mu\text{g/m}^3\) and was still below the standard of PM\(_{10}\) (150 \(\mu\text{g/m}^3\)). It should also be noted that the Gent sampler will under estimate PM\(_{2.5}\) because 50% collection point is closer to 2.2 \(\mu\text{m}\) and not 2.5 \(\mu\text{m}\) [18]. From the results of PM\(_{2.5}\) in Bandung during 2012-2013, there is strong potensial for adverse public health effects. While, the annual averages of PM\(_{10}\) mass were lower than national standard. The
PM$_{10}$ level obtained from this study was also lower than the values reported for other cities such as Serpong Tangerang and Semarang located in west and central Java [19,20].

Twenty-four hours PM$_{2.5}$ and PM$_{10}$ levels at Bandung site were below the 24-hours Indonesian National Ambient Air Quality standards for PM$_{2.5}$ and PM$_{10}$ (65 and 150 µg/m$^3$). The daily mass concentration of PM$_{2.5}$ from this study was also lower than the values reported for residential sites in Serpong West Java, where the mean values for PM$_{10}$ in 2008 from four residential sites ranged from 39.9 to 47.7 µg/m$^3$ [20]. The mass concentration varied quite substantially from one day to the next as manifested by the high standard deviations in the averages. The daily mass concentrations of PM$_{2.5}$ in the wet season (November to March) are lower than in the dry season (April to October) which could be caused by the influence of meteorological parameters such as rainfall. Use of more motor vehicles, industry and dense population might be a major factor for pollution in Bandung.

In 2012-2013, the sampling sites was expanded to 12 cities which covered several big cities in Indonesia namely Ambon, Bandung, Denpasar, Jakarta, Jayapura, Makassar, Palangka Raya, Pekanbaru, Semarang, Serpong, Surabaya, and Yogyakarta. Sampling location development was continuously carried out and in 2015 there were 17 sites involving 16 cities i.e. Ambon, Bandung, Balikpapan, Denpasar, Jakarta, Jayapura, Makassar, Manado, Medan, Matarram, Palangka Raya, Pekanbaru, Semarang, Serpong, Surabaya, dan Yogyakarta. All 17 sites are still running and are expected to continue at least until 2019. Figure 2 presents the distribution of PM$_{2.5}$ concentrations in 2013 for Bandung site compared to 12 other cities. It can be shown that the average PM$_{2.5}$ concentration of several other cities such as Jakarta, Pekanbaru, Surabaya were higher than Bandung.

![Figure 1. PM$_{2.5}$ and PM$_{2.5-10}$ concentration in Bandung, Indonesia](image)
Figure 2. Box and whisker plot of PM$_{2.5}$ concentration 2013 at the 12 sites in Indonesia

The annual average of PM$_{2.5}$ at Surabaya over the period of 2012 to 2013 were 20.71 and 14.55, respectively. While, the annual average of PM$_{10}$ were 51.29, and 29.35. The annual average of PM$_{2.5}$ at Surabaya in 2012 was also higher than the value in several urban areas in Indonesia over the period of 2011 as reported by Santoso [21].

The average of black carbon concentration in PM$_{2.5}$ Bandung during 2012-2013 was 3.10 $\mu$g/m$^3$ and the average percentages of BC in PM$_{2.5}$ was 21.81%. The results showed that the concentration of BC was slightly increased compared to previous results on 2011 (3.05 $\mu$g/m$^3$) [21]. The trend of black carbon concentration obtained from this study is similar to that observed in the airborne particulate matter mass concentration variations. Black carbon is produced during incomplete burning, and the fine fractions are also mostly produced in high-temperature processes. They behave in a similar way with respect to suspension time and dispersion. The production of black carbon is uniquely linked to the combustion of fossil fuel, vehicular exhaust, and biomass burning. The black carbon concentrations are defined based on the amount of reflected light that is absorbed by the filter sample and an assumed mass absorption coefficient. Hence, quantitative black carbon data can be used with other elemental data for predicting the possible source of airborne particulate matter and its apportionment.

Black carbon sources in Bandung have been previously studied by Santoso and showed that the important black carbon sources were motor vehicles and biomass burning [17]. While, for Surabaya, the average and range concentration of BC were 3.47 and 0.67 to 7.43 $\mu$g/m$^3$. The average ratio of BC concentrations compared to the PM$_{2.5}$ was 22.6 %. The highest BC concentration was found in June 2012, it could be due to forest fires from sorounding areas of Surabaya.

Elemental analysis of the APM samples were performs by nuclear analytical methods. To assure that the analytical results generated by INAA were accurate and precise, the NIST standard reference material (SRM) 1648 airborne particulate matter were analyzed in the same experimental conditions that is used in the sample analysis. Several elements in the SRM 1648 were detected and the results were then compared with its certificate values as shown in Table 1. These analysis results had a good agreement with the value quoted in the NIST certificate. The ratio between the analysis value and the certificate indicates the values with a ratio between 0.88-1.22. The concentrations of most elements are consistently within the uncertainties of the certified values [4].
### Table 1. Method validation of INAA using NIST SRM 1648 airborne particulate matter [4]

| Element | Unit     | This work \(X^a\pm SD^b\) | Certificate value (NIST value)\(^c\) |
|---------|----------|-----------------------------|--------------------------------------|
| Al      | %        | 3.43 ± 0.12                 | 3.42 ± 0.11                           |
| As      | mg/kg    | 124 ± 8.5                   | 115 ± 10                              |
| Br      | mg/kg    | 445 ± 14                    | 500                                  |
| Cl      | %        | 0.45 ± 0.03                 | 0.45                                  |
| Co      | mg/kg    | 18 ± 2.4                    | 18                                   |
| Cr      | mg/kg    | 378 ± 84                    | 403 ± 12                              |
| Cs      | mg/kg    | 3.67 ± 0.13                 | 3                                    |
| Fe      | %        | 3.98 ± 0.38                 | 3.91 ± 0.10                           |
| I       | mg/kg    | 19 ± 2                      | 20                                   |
| La      | mg/kg    | 37 ± 6                      | 42                                   |
| Mn      | mg/kg    | 788 ± 27                    | 786 ± 17                              |
| Na      | %        | 0.403 ± 0.031               | 0.425 ± 0.002                         |
| Sb      | mg/kg    | 45.8 ± 2.2                  | 45                                   |
| Sc      | mg/kg    | 6.74 ± 0.28                 | 7                                    |
| Sm      | mg/kg    | 4.5 ± 0.85                  | 4.4                                  |
| Ti      | %        | 0.41 ± 0.05                 | 0.40                                 |
| V       | mg/kg    | 126 ± 7                     | 127 ± 7                               |
| Zn      | %        | 0.418 ± 0.024               | 0.476 ± 0.014                         |

\(^a\) mean value  
\(^b\) one standard deviation  
\(^c\) NIST does not provide uncertainties for uncertified elements

The elemental concentration measured for PM\(_{2.5}\) Bandung samples collected during 2004 are shown in Figure 3. The INAA technique was performed to analyse more than 20 elements. In Figure 4, the analysed data for elemental concentrations by PIXE are also presented [4]. PIXE provides elemental information on a broad range of elements. Some elements have a large number of fit error (%) or values below detection limit, therefore only about 20 measured elements were used in the data analysis. Some elements that cannot easily be analysed by INAA such as Si and Pb are well analysed by PIXE. On the contrary, other elements such as I, Na and K were better analysed by INAA than PIXE. By PIXE, the fit error has resulted more than 50% for I, Na, V and Co. Elements Cs, Co, Sb, Sc, Se, Sm, La, Hg were also well analysed by INAA. The PIXE results obtained in Fig. 4 showed that S is the major elemental species in fine size particulate samples (PM\(_{2.5}\)), therefore elemental analyzed for sulfur were important to carried out. The range of elements observed indicates a variety of different fine particle sources [4].
The comparison between PIXE and NAA has been studied by others and the ratio of the fit for NAA to PIXE on the same samples is 0.97±0.01 with the coefficient of least squares fit is R^2=0.99. This results was excellent agreement as the analyses were carried out in different laboratories. This results and other published studies provides great confidences that the nuclear techniques are suitable for filter samples analysis [21], [22], [23], [24], [25], [26], [27], [28].

The XRF thecniques was used to analyse for elements Na, Mg, Al, Si, S, K, Ca, Ti, Mn, Fe, Zn, and Pb. In Figure 5 shows the whisker plot of multi elements concentration for PM2.5 at Surabaya site over the period of 2012-2015. The high concentration of crustel elements were observed from the samples collected during the eruption episode, especially from mount Kelud at February 2014. In Figure 5 could be shown that lead concentration was high in the PM2.5 with the maximum concentrations was 2.78 µg/m^3. This value was significantly higher and several data fall to the 24 hours national ambient air quality standard of Indonesia for lead in total suspended particulate matter (2 µg/m^3). These results revealed that lead concentration in Surabaya were much higher compared to other cities in Asia countries [29] and even higher than Tangerang that already indicated polluted with lead [20]. From Figure 5, it can be shown that besides the high Pb concentration, it is also detected that the Zn concentration in PM2.5 in Surabaya is also high. In Figure 6, a comparison of Zn concentrations in 17 cities showed that Zn concentrations in Surabaya are significantly different from other cities. The source of Zn pollution can be caused by motor vehicle emissions and industrial activities such as galvanizing operations, non-ferrous metal smelting. For this reason, more detailed research is needed to accurately trace the source of these emissions.
The EDXRF and PIXE characterization still have certain limitations as an elemental analysis technique without offering any information on the chemical environment of the analyte. Chemical speciation from some elements is needed to assess the impact of toxic elements emission to the environment and to get better understanding of the involved environmental processes. NAA, PIXE and EDXRF cannot offer oxidation state analysis of the contained elements. Chemical speciation studies are needed to improve the identication of pollution sources and source apportionment models, to get better understanding of the types of environmental physicochemical processes that are responsible for the presence of certain chemical species in APM samples.

Preliminary study for chemical speciation was done for APM samples using synchrotron facilities in Elettra Italy. The selected APM sample collected from industrial area at Surabaya was analysed using X-ray absorption near-edge structure (XANES) for Zn speciation with 20s/step. The measurement was continued for analyzing several standards foil with 1s/step. XRF scanning was then applied for SRM NIST 2783 blank filter and APM using the similar procedures with energy of 13.5 keV, 100s/step. The results of Zn speciation of APM samples were shown in Figure 7. The speciation
spectrum of Zn shown that Zn spectrum of APM samples were more likely to ZnSO$_4$.7H$_2$O spectrum than any other Zn species. This result will strengthen the determination of Zn pollutant sources.

Analysis of chemical species from key trace elements such as As, Cr and Se is very important and generally below the detection limits of ED-XRF and PIXE. Furthermore, the oxidation state analysis of other trace elements such as Cr, and As are also required. The information related to the oxidation state of the trace elements is critical for evaluating the transport, deposition, and environmental impact of these element emissions. It would also be interesting to investigate the chemical speciation of various other trace elements to get better information related to health effects. Therefore further research focusing on chemical speciation for APM samples is needed to get a better understanding of air pollutant sources.

Figure 7. Zn speciation spectrum for APM samples collected in Surabaya

The results obtained showed that nuclear analytical techniques are a very accurate and unique method for characterizing multi-elements in airborne particulate samples. NATs are very sensitive and have multi-elemental analysis capabilities so that analysis can be done very quickly and accurately. In addition, NATs are non-destructive analysis technique, so that after analysis, the sample can still be stored as a sample archive and the analysis can be repeated if needed. This makes NATs very suitable for analyzing airborne particulate samples compared to other conventional methods which are mostly destructive methods.

4. Conclusion
Characterization of airborne particulate samples in Indonesia using INAA, PIXE, XRF and XANES provides comprehensive results in explaining the characteristics of multi-element chemical species and their oxidation state. This capability can then be applied to determine source fingerprints, possible particle sources and to get better information related to their impact on human health.

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References

[1] BAPPENAS, National Development Planning Agency. National/Local Strategy and Action Plan for Urban Air Quality Improvement; 2006
[2] N. Martinelli, O. Olivieri, D. Girelli. Air particulate matter and cardiovascular disease: a narrative review. European Journal of internal medicine, 24, 2013, 295-302
[3] Haryanto, B. (2018). Climate Change and Urban Air Pollution Health Impacts in Indonesia Climate Change and Urban Air Pollution Health Impacts in Indonesia, (January). https://doi.org/10.1007/978-3-319-61346-8
[4] Muhayatun Santoso, Diah Dwiana L, Philip K Hopke and Andreas Markwitz, Nuclear Analytical Technique INAA and PIXE Application for Characterization of Airborne Particulate Matter in Indonesia, Journal of Applied Sciences in Environmental Sanitation, 5(2), 2010, 203-222
[5] D.D. Cohen, E. Stelcer, A. Atanacio, J. Crawford. The application of IBA techniques to air pollution source fingerprinting and source apportionment. Nuclear instruments and methods in physics research B. 318, 2014, 113-118
[6] W. Maenhaut. X-Ray fluorescence and emission I particle-induced X-Ray emission, Elsevier Reference Module in Chemistry, Moleculat sciences and chemical engineering, 2013. Doi: 10.1016/B978-0-12-409547-2.00580-1
[7] S.A. Rahman, et al. A long term study on characterization and source apportionment of particulate pollution in Klang Valley, Kuala lumpur, Aerosol and air quality research, 15, 2015, 2291-2304
[8] Muhayatun Santoso, Diah Dwiana Lestiani, Endah Damastuti, Syukria Kurniawati, John W. Bennett, Juan Jose Leani, Mateusz Czyzycki, Alessandro Migliori, Ja’nos Osa’n, Andreas Germanos Karydas, Trace elements and As speciation analysis of fly ash samples from an Indonesian coal power plant by means of neutron activation analysis and synchrotron based techniques, J Radioanal Nucl Chem, 08 March 2016, DOI 10.1007/s10967-016-4755-z
[9] Diah Dwiana Lestiani, Muhayatun Santoso, Syukria K, Natalia Adventini, Djoko P. Characteristic of Feed coal and particulate matter in the vicinity of coal-fired power plant in Cilacap, Central Java, Indonesia. Procedia Chemistry, 16 (2015), 216-221
[10] Pakkanen, T.A., Kerminen, V., Oajanen, C.H., Hillamo, R.E., Aarnio, P., Koskentalo, T. Atmospheric Black carbon in Helsinki. Atmos. Environ. 34: 2000, 1497-1506. doi:10.1016/S1352-2310(99)00344-1
[11] Lestiani DD, Santoso M, Adventini N. Application of neutron activation analysis in characterization of environmental SRM samples. Indon J Chem 9: 2009, 231–235
[12] Greenberg RR, Bode P, Fernandes E (2011) Neutron activation analysis: a primary method of measurement. Spectrochimica Acta Part B 66:2011, 193–241
[13] Muhayatun Santoso, Diah Dwiana, Application of energy Dispersive X-Ray Fluorescence (EDXRF) In Supporting National Program of Air Quality Program of air Quality Improvement In Indonesia, XRF Newsletter Newsletter of the IAEA Laboratories, Seibersdorf, Issue No 26, April 2014
[14] Trompetter WJ, Markwitz A, Davy P, Air particulate research capability at the New Zealand ion beam analysis facilities using PIXE and IBA techniques. Int. J.PIXE 15: 2005, 249-255
[15] Osa’n J, To’ro’k B, To’ro’k S, Jones KW (1997) Study of chemical state of toxic metals during the life cycle of fly ash using X-ray absorption near-edge structure. X-Ray Spectrum 26:37–44
[16] Santoso, M, Lestiani, D. D., Kurniawati, S., Damastuti, E., Kusmartini, I., Prakoso, D., … Rita. (2019). Elemental Composition of Particulate Matter Air Pollution Collected Around Industrial Area in East Java. IOP Conference Series: Earth and Environmental Science, 303, 012036. https://doi.org/10.1088/1755-1315/303/1/012036
[17] Santoso, M., Hopke, P.K., Hidayat, A., Dwiana, D., 2008. Source identification of atmospheric aerosol at urban and suburban sites in Indonesia by positive matrix factorization. Science of Total Environ. 397:229-237.

[18] Hopke PK, Xie Y, Raunemaa T, Biegalski S, Landsberger S, Maenhaut W, Artaxo P, C. D. (1997). Characterization of the Gent stacked filter unit PM10 sampler. Aerosol Sci Technol, 27, 726–735

[19] Browne, D.R., Husni, A., Risk, M.J., 1999. Airborne lead and particulate levels in Semarang, Indonesia and potential health impact, Science of the Total Environment, 227:145–154

[20] Santoso, M., Lestiani, D.D., Mukhtar, R., Hamonangan, E., Syafrul, H., Markwitz, A., and Hopke, P.K. 2011. Preliminary Study of the Sources of Ambient Air Pollution in Serpong, Indonesia, Atmospheric Pollution Research, 2:190-196.

[21] Muhayatun Santoso, Diah Dwiana Lestiani, Philip K. Hopke. Atmospheric Black Carbon in PM$_{2.5}$ in Indonesian Cities, Journal of the Air & Waste Management Association Vol. 63 (9), 1022-1025, 2013

[22] Biswas, S. K., Tarafdar, S. A., Islam, A., Khaliquzzaman, M., Tervahattu, H.and Kupiainen, K. 2003. Impact of unleaded gasoline introduction on the concentration of lead in the air of Dhaka, Bangladesh. J. Air and Waste Management Association. 53: 1355-1362.

[23] Chueinta, W., Hopke,P.K., Paatero, P. 2000. Investigation of sources of atmospheric aerosol at urban and suburbun residential areas in Thailand by Positive matrix factorization. Atmospheric Environment 34:3319-3329

[24] Begum, B.A., Biswas, S.K., Kim, E., Hopke, P.K., Khaliquzzaman, M. 2005. Investigation of sources of atmospheric aerosol at hot spot area in Dhaka, Bangladesh. J. Air Waste Manage. 55:227 – 240.

[25] Chung, Y.S., Kim, S.H., Moon, J.H., Kim, Y.J., Lim, J.M., Lee, J.H. 2005. Source identification and long term monitoring of airborne particulate matter PM2.5/PM10 in an urban region of Korea. J Radioanal Nucl Chem. 267:35-48.

[26] Hien, P.D., Bac, V.T., Thinh N.T.H. 2005. Investigation of sulfate and nitrate formation on mineral dust particles by receptor modeling. Atmos Environ. 39:7231 – 7239

[27] Hopke, P.K., David D. Cohen, Bilkis A. Begum, Swapan K. Biswas, Bangfa Ni, Gauri Girish Pandit, Muhayatun Santoso, Yong-Sam Chung, Perry Davy, Andreas Markwitz, Shahida Waheed, Naila Siddique, Flora L. Santos, Preciosa Corazon B. Pabroa, Manikkuwadura Consy S.S., Wanna Wimolwattanapun, Supamatthree Bunprapol, Thu Bac Vuong, Pham Duy Hien, Andrzej Markowicz.,2008. Urban air quality in the Asian region. Science of Total Environ. 404:103-112.

[28] Cohen D.D, Grahama M.B, Kondepudi R. 1996 Elemental Analysis by PIXE and other IBA techniques and their application to source fingerprinting of atmospheric fine particles pollution, Nucl. Instr. and Meth. B 109:218-226

[29] Muhayatun Santoso, Diah Dwiana Lestiani, Syukria Kurniawati, A. Markwitz, W. J. Trompetter, B. Barry and P. K. Davy, Long term airborne lead pollution monitoring in Bandung, Indonesia, International Journal of PIXE, Vol. 24, Nos. 3 & 4 (2014) 157–165, DOI: 10.1142/S0129083514400087