Organic Molecular Marker from Regional Biomass Burning—Direct Application to Source Apportionment Model

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Abstract: To reduce fine particulate matter (PM$_{2.5}$) level, the sources of PM$_{2.5}$ in terms of the composition thereof needs to be identified. In this study, the experimental burning of ten types of biomass that are typically used in Republic of Korea, collected at the regional area were to investigate the indicated organic speciation and the results obtained therefrom were applied to the chemical mass balance (CMB) model for the study area. As a result, the organic molecular markers for the biomass burning were identified as they were varying according to chemical speciation of woods and herbaceous plants and depending upon the hard- and soft characteristics of specimens. Based on the source profile from biomass burning, major sources of PM$_{2.5}$ in the study area of the present study appeared as sources of biomass burning, the secondary ions, secondary particulate matters, which is including long-distance transport, wherein the three sources occupied most over 84% of entire PM$_{2.5}$. In regard to the subject area distinguished into residential area and on roads, the portion of the biomass burning appeared higher in residential area than on roads, whereas the generation from vehicles of gasoline engine and burning of meats in restaurants, etc. appeared higher on roads comparing to the residential area.

Keywords: molecular marker; source profiles; source apportionment model

1. Introduction

One of the health risk factors, air pollution, has brought about approximately 3.7 million premature deaths in 2012, and is estimated to be affecting mostly on the mortality due to environmental effects by 2050 [1,2]. PM$_{2.5}$, one of the air pollutants, is a particulate of aerodynamic diameter less than 2.5 µm occupying 96% of those found in human lungs [3]. PM$_{2.5}$ penetrates the gas exchange region of the lungs and enters the circulatory system via passing through the respiratory barrier thereby spreads over the human body [4–6]. The Guidelines of Air Quality Management of World Health Organization recommend the employment of PM$_{2.5}$ instead of PM$_{10}$ as an indicator identifying air pollution; the public interest in the risk of PM$_{2.5}$ was increasing thereby [1].

To reduce the amount of PM$_{2.5}$, the sources of PM$_{2.5}$ in terms of the composition thereof needs to be identified. Depending on the sources of PM$_{2.5}$, the attribute of PM$_{2.5}$ can be distinguished into the
artificial- and natural sources by which it can be divided into the primary matter directly discharged from sources and the secondary matter to be produced by chemical reaction of gas phase materials according to the photochemical reaction. The components of PM$_{2.5}$ consist mainly of carbons, such as organic mass (OM) including organic carbon (OC) and elemental carbon (EC), heavy metals and water soluble ions, etc. [7–9]. Less than 30% of organic compounds among the components can be identified as individual organic species wherein the part of materials of organic species exhibit very high source specificity [10]. These substances can be exploited as molecular markers to estimate the contribution of each source which are assigned in the model devised to identify sources of PM$_{2.5}$ [11,12]. Representative molecular markers comprise levoglucosan (pyrolysis of biomass), hopanes and steranes (combustion of fossil fuels) and cholesterol (combustion of meats) [10,12,13]. In South Korea, although use of biomass materials, such as pine trees, as the fuel of boilers has been growing in rural areas, in which farmers use vinyl greenhouses to raise fruits, vegetables and tropical plants during winter. However, the major source of serious air pollution problems in rural and neighboring urban areas is the natural forest fire during wintertime in the dry condition. The other source of air pollution due to biomass burning is the open-burning of agricultural crop residues after harvest to prepare the next cultivation even though the government prohibited the burning activities. As discussed above, the chemical properties of organic aerosol particles from biomass burning emissions vary significantly depending on the burning phase and biomass type. It is still a major challenge to investigate the chemical properties.

Distinguished sources of air pollutants can be employed as basic data for the reduction of emission of sources of air pollutants by which the contribution of air pollutants can be reduced. In general, diverse kinds of acceptance model techniques are used for the distribution of sources of air pollutants. Representative models for the distribution of sources of air pollutants comprise the principal component analysis (PCA), enrichment factors (EFs), chemical mass balance (CMB), positive matrix factorization (PMF), empirical orthogonal functions (EOF), multiple regression, Fourier transformation time series and other multivariate analysis, etc. [13–23]. Among them, the CMB model is most widely used to identify sources of PM$_{2.5}$ [24]. However, the CMB model accompanies uncertainties originated from errors for arbitrary measurements or errors of input variables (organic molecular markers) beyond analytic results and inputted molecular markers. Thus, component analysis of PM$_{2.5}$ and accuracy of input variables are needed for the CMB model [25].

The present study intends for the identification of sources of creation of PM$_{2.5}$ by employing the CMB model. For which, the 160 kinds of chemical components, comprising EC, OC, water soluble organic carbon (WSOC), water insoluble organic carbon (WIOC) and water soluble ions, etc. were analyzed after collecting PM$_{2.5}$ from the subject area of the present study. In addition, the experiments of burning of 10 kinds of biomass were carried out to secure accuracy of CMB model, and the results obtained therefrom were applied to the CMB model. The results obtained from the present study are expected to be employed as basic data for the distribution of sources of PM$_{2.5}$.

2. Materials and Methods

A biomass burning chamber consists of three parts (i.e., a combustion chamber (0.54 m$^3$), primary dilution chamber (3.75 m$^3$) and secondary dilution chamber (0.04 m$^3$)). It was employed for generation of forest tree types (6) and agricultural crop residues (4) (Figure 1 and Table 1), which were sampled from rural and regional forest areas in Korea. Zero air was supplied into the combustion chamber using a mass flow controller. About 25 g of biomass for each combustion was loaded on the grid of the combustion stove. The smoke was drawn into a primary (3.75 m$^3$) dilution chamber (1:1), followed by a secondary dilution chamber (0.04 m$^3$) (1:10). PM$_{2.5}$ samples were collected on pre-baked 90-mm quartz-fiber filters, 47-mm quartz-fiber filters and 47-mm Teflon filters (Pall Gellman, Ann Arbor, MI, USA) using 92 L per minute (lpm) medium-volume sampler and a set of low volume samplers, respectively. The detailed operation conditions can be found at the previous publication [26].
2.1. Organic Speciation

For the determination of organic molecular markers, the quartz filter sample was extracted by sonication using dichloromethane for non-polar organic compounds (i.e., Polyaromatic hydrocarbons (PAHs), n-alkanes, cycloalkanes and steranes and hopanes) analyzed using gas chromatography-mass spectrometry (GC-MS) and methanol or purified water for polar organic compounds (i.e., levoglucosan, amino acids, resin acids, alkanoic acids, aromatic diacids and alkane dioic acids) quantified using liquid chromatography-tandem mass spectrometry (LC-MSMS). All data were blank corrected using field blank data. For each nonpolar organic sample, the final volume was adjusted to 500 µL to match the volume of the internal standard (samples and blanks were spiked with internal standards). Underivatized polar organic compounds were analyzed using LC-MSMS with internal standards (e.g., phthalic acid (D4)), the milli-Q water of 5.0 mL (or methanol some polar organic compounds (e.g., phthalates and cholesterol, etc.) was sonicated into the sample tube for the final extract volume. Hydrophilic interaction LC used an Eclipse XDB-C18 4.6-mm ID × 150 mm (5 mm) column as stationary phase with 10-mM ammonium acetate and acetonitrile in milli-Q water. Polar organic compounds was
analyzed in multiple reaction monitoring application for the separation and detection of underivatized compounds. Regression coefficients of determination for seven point calibrations were from higher than 0.998. Absolute method of detection limits were in the range of 1.0–4.6 pg/m³. For all polar organic compounds, the final mass fragment transitions of quantification application such as fragmentor voltage, collision energy, quantifier and qualifier ions, were determined. The detailed analytical condition can be found at the previous study [27–29].

2.2. Analysis of Organic Carbon (OC) and Elemental Carbon (EC)

The OC/EC analysis used in this study used thermal-optical transmittance according to the National Institute of Occupational Safety and Health (NIOSH5040) protocol. The NIOSH5040 protocol consists of three major stages. At the first stage, the sample was heated to 870 °C with He gas, and the second stage it was heated to 870 °C in the presence of O₂. In the final third step, OC and EC were quantified using an internal standard (5% CH₄ in He) for each sample. In the assay process, 2 µg C/µL sucrose (monosaccharide, C₁₂H₂₂O₁₁) was used as external reference material for test and calibration of the equipment condition and quantification. The OC/EC classification of the NIOSH5040 protocol was determined to be the point at which the transmittance of the laser back to the initial transmittance after gradual decrease when it passed through the filter [30].

2.3. Analysis of Water Soluble Total Organic Carbon (WSOC) and Ion Components

The extract was analyzed by total organic carbon (TOC) analyzer to analyze the water soluble total organic carbon (WSOC) of the sample. As with OC, the contamination level and condition of the equipment were checked using the external standard substance of WSOC, 3-mg/L sucrose. The analysis conditions were as follows: 15% (NH₄)₂S₂O₈ and 6-M H₃PO₄ were used as the oxidizing agent and the buffer solution, respectively, and analyzed by mixing them at the flow rates of 0.50 µL/min and 2.00 µL/min, respectively. Additionally, Inorganic Carbon Remover (ICR) was used to prevent interference with inorganic carbon. The extract was analyzed, and ion components were detected. Ionic compounds were analyzed using ion chromatography (Metrohm 883 Switzerland). For the cation, a Metrohm Metrosep C₄ 250/4.0 column was used. As the eluent, 5-mM HNO₃ at a flow rate of 0.60 mL/min was used. For anions, a Metrohm Metrosep A Supp 5 150/4.0 column was used. As the eluent, 3.20-mM Na₂CO₃ and 1.00-mM NaHCO₃ were mixed. The flow rate was 0.70 mL/min and H₂SO₄ (50 mM) suppressor was used. The amount of sample injected for anion and cation analysis was 250 µL each [30,31].

2.4. Ambient PM₂.₅ Sampling

Two sites (i.e., residential and roadside site) were simultaneously operated to collect 24-integrated PM₂.₅ samples from May 9 to 13 (spring), August 4 to 8 (summer), October 11 to 13 (fall) in 2016 and January 8 to 10 in 2017 (winter). PM₂.₅ samples were collected using the same as samplers in the biomass burning chamber for each site. Samples were shipped and stored frozen until analysis. The residential site is located on the campus of the Gwangju Institute of Science and Technology (GIST) (35°13’41.1” N and 126°50’36.3” E) in Korea. The site is situated about 8 km from the city center and is surrounded by agricultural, residential and commercial areas. Road site (35°18’21.1” N and 126°88’86.3” E) is closely located at the main road with heavy traffic surrounded by several businesses and restaurants and is also close to a main highway.

2.5. Source Apportionment Methods

The CMB model (EPA-CMB8.2) was applied to the results obtained during the intensive sampling campaign [32,33]. The CMB develops a solution based on a linear summation of products at a receptor location based on the abundance of source profiles and source contributions. The CMB model attempts to fit ambient speciated results from residential and roadside sites to a specified group of sources with corresponding molecular markers. In this study, uncertainties for CMB in molecular marker data
points were defined as the maximum of two functions of spike recoveries, detection limits, and load blank standard deviations. The source profiles used in the study except the biomass burning is the profiles in the previous study [28]. The detailed CMB method can be found elsewhere [28].

3. Results and Discussion

3.1. Source Profile of Biomass Burning

Table 2 and Figure 2 show the emission in chemical classes of PM$_{2.5}$ from burning of woods and agricultural byproducts. The burning materials appeared according to characteristics thereof; approximately 48%, 7% and 6% of chemical components that consist of PM$_{2.5}$ appeared as OC, ionic compounds and EC, respectively. Based on results of previously conducted studies, approximately 49% of chemical components except for OC, EC and ionic chemical components, are estimated to be comprised of heavy metals, tiny amount of moisture, H, N, S and O, etc. that consist of organic substances other than carbon components [7–9].

Table 2. Distribution of chemical abundances in fine particulate matter (PM$_{2.5}$) mass.

| Unit: µg/m$^3$ | Forest Tree Types | Agricultural Crop Residues |
|----------------|------------------|-----------------------------|
|                | Pine Needles     | Pine Stem                   | Ginkgo Leaves | Maple Leaves | Cherry Leaves | Cherry Stem | Rice Straw | Soybean Stem | Green Perilla Stem | Red Pepper Stem |
| PM$_{2.5}$     | 99,816           | 78,438                      | 102,111      | 118,201      | 86,759        | 43,808      | 77,252     | 107,997      | 69,945           | 40,805           |
| OC             | 53,514           | 28,566                      | 53,794       | 60,307       | 49,993        | 14,457      | 41,548     | 55,554       | 27,886           | 11,602           |
| EC             | 6496             | 8587                        | 2673         | 2886         | 7446          | 2649        | 1392       | 5485         | 10,584           | 4719             |
| Ions           | 4861             | 4219                        | 5116         | 3369         | 7004          | 4890        | 2756       | 5527         | 9586             | 7029             |
| Class-OC       |                  |                              |              |              |               |             |            |              |                  |                  |
| WIOC           | 19,785           | 2284                        | 30,458       | 30,882       | 20,519        | 1678        | 9482       | 13,139       | 1764             | 725              |
| WSOC           | 33,728           | 26,281                      | 23,335       | 29,425       | 29,474        | 12,779      | 32,066     | 42,415       | 26,121           | 10,877           |
| Class-WIOC     |                  |                              |              |              |               |             |            |              |                  |                  |
| PAHs           | 1179             | 653                         | 134          | 172          | 191           | 201         | 170        | 183          | 426              | 105              |
| Alkanes        | 291              | 102                         | 969          | 1006         | 729           | 302         | 797        | 697          | 167              | 128              |
| Class-WSOC     |                  |                              |              |              |               |             |            |              |                  |                  |
| alkanoic acids | 6311             | 2750                        | 7424         | 4848         | 3593          | 1252        | 6644       | 5986         | 1006             | 570              |
| benzene carboxylic acid | 14       | 19                           | 10            | 16           | 26            | 18          | 0          | 31           | 30               | 10               |
| Di-carboxylic acid | 352         | 124                         | 80           | 137          | 94            | 62          | 196        | 230          | 32               | 19               |
| Amino acids    | 32               | 10                           | 28           | 37           | 8             | 11          | 81         | 67           | 11               | 11               |
| levoglucosan   | 1751             | 1950                        | 1452         | 1783         | 2043          | 2274        | 1499       | 1656         | 1747             | 1308             |
| Class-Ions     |                  |                              |              |              |               |             |            |              |                  |                  |
| Potassium      | 660              | 1326                        | 2004         | 507          | 3298          | 1830        | 626        | 1382         | 4433             | 3424             |
| Sulfate        | 2040             | 1356                        | 1436         | 1312         | 1488          | 1230        | 1152       | 1682         | 2996             | 1742             |
| Nitrate        | 1680             | 964                         | 957          | 1014         | 1138          | 960         | 701        | 1682         | 1797             | 931              |
| Ammonium       | 480              | 573                         | 718          | 537          | 1080          | 870         | 276        | 781          | 359              | 931              |

To estimate the contents of H, N, S and O except for carbon components, the ratios of OM/OC, based on molecular weight of 114 individual OC compounds which were analyzed in the present study, were calculated. From calculations of OM/OC, the WIOC appeared as 1.1 while the WSOC appeared as 1.5. Approximately 66% of chemical components consisting of PM$_{2.5}$ appeared as OC based organic matters from the application of the ratio of OM/OC to calculations of WIOC and WSOC, while the occupancy of components of OC, EC and ionic chemical components in PM$_{2.5}$ appeared as 79%. The correlation of the ratio of OM/OC with PM$_{2.5}$ was identified wherein the correlation coefficient more than 0.85 was found thereby the estimation of chemical components consisting of PM$_{2.5}$ through employing the ratio of OM/OC was identified reliable as shown in Figure 2.
As a means to appraise the source of emission of PM$_{2.5}$, the ratio of OC/EC is used [34]. The ratio of OC/EC of PM$_{2.5}$ resulted from the burning of coal has been known to be distributing in the range 1.6–3 [35,36] while the ratio of OC/EC of PM$_{2.5}$ resulted from combustion of engine has been known to be distributing in the range 0.5–1.3 [16,37]. The ratio of OC/EC of PM$_{2.5}$ emitted from the biomass burning has been known over 3 which is higher than those of other sources; according to part of previously conducted studies, the ratio of OC/EC appeared higher than 12 of rice straw and 24 of wheat straw [37,38]. The ratio of OC/EC resulted from the biomass burning appeared distributing in the range 2.46–29.85 wherein the mean ratio thereof was 10.98. The ratio of OC/EC of 8 specimens among 10 specimens of analysis appeared over 3.0 and corresponded to results of previous studies however the ratios of OC/EC of stems of red-pepper and green perilla appeared below 3.0 suggesting different consequences from results of previous studies. To identify the causes behind the consequences, the specimens were distinguished into the hard ones of higher density (pine trees, cherry tree, red-pepper stems and stems of green perilla) and soft ones of lower density (pine needles, gingko leaves, maple leaves, cherry leaves, rice straws and stems of beans). The resulting ratio of 15.99 of OC/EC of soft specimens appeared relatively high while the ratio of 3.47 of OC/EC of hard specimens appeared lower than that of soft specimens.

The four chemical components of K$^+$, SO$_4^{2-}$, NO$_3^-$ and NH$_4^+$, constituting PM$_{2.5}$, were analyzed as ionic components. Contents of respective components of PM$_{2.5}$ appeared as approximately 2.36% of K$^+$, 1.99% of SO$_4^{2-}$, 1.43% of NO$_3^-$ and 0.8% of NH$_4^+$. Among them, K$^+$ has been known as a major indicator ingredient of biomass burning; the level of content of K$^+$ contained in dried woods has been known approximately over 0.1%, over 0.2% for dried herbaceous plant and over 3% for crops such as olive, etc. [39]. The K$^+$ contained in crops, is emitted as KCl, KOH or K$^+$ at temperature over 1000 K [40] and according to previously conducted studies, the K$^+$ in PM$_{2.5}$, discharged from biomass burning, has been known to be contained 1%–10% in wheat straw and stems of maize and over 10% in rice straws [41]. The content of K$^+$ analyzed in the present study appeared with lower levels of average 1.82% in the six woods and average 3.33% in herbaceous plants comparing to results reported from previous studies. In particular, the specimens of rice straw, analyzed in the present study, contained approximately 0.81% of K$^+$ showing significant difference from results of previous studies.

**Figure 2.** Relative chemical abundances in PM$_{2.5}$ and scatterplots between measured and reconstructed PM$_{2.5}$ mass from burning of forest tree types and agricultural crop residues byproducts.
Generally, in the case of using K⁺ as an indicator material of the biomass burning, the ratio of K⁺/EC is used [41]. Table 3 shows the ratio of K⁺/EC derived from the previously conducted studies and from the present study. As presented in the table, the ratio of K⁺/EC of herbaceous plant, employed for the present study, appeared distributing in the lower range 0.25–0.73 comparing to the ratio of K⁺/EC of 1.12–3.45 of herbaceous plant employed for the previous studies. In particular, the ratio of K⁺/EC of rice straw, which was predicted as pseudo-crop, was 3.45 in the previous studies exhibiting significant difference from 0.45 of the present study. On the contrary, the ratio of K⁺/EC of woods of the present study appeared distributing in the range 0.1–0.75 which were similar to those of 0.19 and 0.76 of previously conducted studies. The similarity (of woods) and difference (of herbaceous plant) in the ratio of K⁺/EC of the present study from those of previously conducted studies were attributed to the differences in components of specimens, species and corresponding cultivation environment.

In the present study, the leaves and branches of the part of specimens of woods were distinguished wherein the ratio of K⁺/EC in branches of pine tree and cherry tree appeared approximately 50% higher than those in the leaves thereof. This suggests the ratio of K⁺/EC can be varied according to the ratio of composition of leaves and branches to be burnt, though they belong to the same kind of biomass of identical species. In addition, the content of K⁺ in leaves and branches of cherry tree appeared higher than other woods with respective values of 3.80% and 4.18%, while the content of K⁺ in stems of green perilla and red-pepper appeared 6.34% and 8.39%, respectively, suggesting the contents of K⁺ appeared distributing in the variable range of 0.43%–8.39% according to species of crops. Additionally, the K⁺, contained in plants, is affected by microorganisms and amount of potassium in soil. Potassium is the one of major nutrients for the growth of plants, the representative element of fertilizer. Water soluble potassium among fertilizer elements spread over soils are absorbed by crops, whereas the solidified potassium are absorbed by crops via microorganisms enabling the solubilization of potassium [42]. Therefore, the amount of potassium, contained in plants, is significantly dependent on the cultivation environment of plants. In the meantime, the red-pepper in Korea is regarded as one of the crops creating the highest value added as well as essential seasoning agent for which the area of cultivation of 32,865 ha in 2018 for red-pepper appeared higher than that of other flavor vegetables [43]. In addition, since the red-peppers are cultivated in an open field, it is included as the representative one of burning of agricultural byproducts in the registry of national atmospheric pollutants in Korea. Based on these facts, the kinds of species and cultivation environment of crops in each country, and the emission of K⁺ from respective crops need to be identified preemptively for the employment of K⁺ as an indicator material of the biomass burning. This is because the crops to be cultivated in countries are different according to respective dietary habits and the emission of K⁺ varies significantly according to types of species of crops cultivated.

The OC, occupying the highest portion among the components of PM₂.₅, was classified into WIOC and WSOC, wherein the ratio of WIOC to WSOC appeared as approximately 1.2; the occupancies of WIOC and WSOC in PM₂.₅ were approximately 16% and 32%, respectively. Further, for the specimens of woods, the weight percentage of WIOC and WSOC to total weight of PM₂.₅ appeared approximately 20.0% and 29.2%, respectively, whereas the weight percentage of WIOC and WSOC to total weight of PM₂.₅ in herbaceous plant appeared approximately 8.5% and 37.6%, respectively. That is, the WIOC appeared higher in woods than in herbaceous plant, whereas the WSOC appeared higher in herbaceous plant than in woods. To determine the concentration of components in WIOC and WSOC, the 114 organic compounds, comprising the 23 compounds of PAHs and 33 compounds of alkanes were analyzed for the analysis of WIOC, as well as the 27 compounds of alkanes, 8 compounds of benzene carboxylic acid, 7 compounds of di-carboxylic acid, 15 compounds of amino acids and levoglucosan, were analyzed for the analysis of WSOC. The results of the analysis are presented in Figures 3 and 4. A total of 56 compounds of analysis of the PAHs and alkanes occupied approximately 7% of entire WIOC, wherein the weight percentage of PAHs and alkanes were 0.47% and 0.64%, respectively, to the weight of PM₂.₅. PAHs appeared as in the order of phenanthrene > fluoranthene > pyrene; the emission of PAHs from woods appeared higher comparing to that from
the herbaceous plant. In particular, retene was detected from the 3 ones among the 4 herbaceous plants with corresponding average concentration of 0.07 mg/g-OC, whereas the wood was detected from all 8 crops with corresponding average concentration of 0.92 mg/g-OC, which was higher than that of the herbaceous plant. In particular, retene, which is emitted from woods, was discharged highly from specimens of pine tree wherein the concentration in pine needle and in stalk exhibited 1.07 mg/g-OC and 6.11 mg/g-OC, respectively. For the case of alkanes, the detected ratios from woods and herbaceous plants appeared varying according to compounds of analysis. In the analyses from C_{11} to C_{29}, the concentrations of wood exhibited higher emission than concentrations of herbaceous plant, whereas in the analyses from C_{30} to C_{40}, the concentrations of herbaceous plant manifested characteristics of higher emission than that of concentrations of wood. In addition, by the chemical classification into hard- and soft ones, the 5 compounds of analysis among alkanes (n-tridecane, n-tetradecane, n-pentadecane, n-hexadecane and norpristane) appeared only from the soft ones.

Table 3. Ratios of \( K^+ \)/elemental carbon (EC) for crop residue emissions from this study compared to similar measurements reported elsewhere.

| Type of Biomass          | Measurement Approach | PM Size | \( K^+/EC \) | References          |
|--------------------------|----------------------|---------|--------------|---------------------|
| Wood (pine needles)      | chamber              | PM_{2.5}| 0.10         | this study          |
| Wood (pine stem)         | chamber              | PM_{2.5}| 0.15         | this study          |
| Wood (ginkgo leaves)     | chamber              | PM_{2.5}| 0.75         | this study          |
| Wood (maple leaves)      | chamber              | PM_{2.5}| 0.18         | this study          |
| Wood (cherry leaves)     | chamber              | PM_{2.5}| 0.44         | this study          |
| Wood (cherry stem)       | chamber              | PM_{2.5}| 0.69         | this study          |
| Rice straw               | chamber              | PM_{2.5}| 0.45         | this study          |
| Soybean stem             | chamber              | PM_{2.5}| 0.25         | this study          |
| Green perilla stem       | chamber              | PM_{2.5}| 0.42         | this study          |
| Red pepper stem          | chamber              | PM_{2.5}| 0.73         | this study          |
| Wheat straw              | chamber              | PM_{2.5}| 2.26         | Ni et al. 2017      |
| Rice straw               | chamber              | PM_{2.5}| 3.45         | Ni et al. 2017      |
| Corn stalk               | chamber              | PM_{2.5}| 1.12         | Ni et al. 2017      |
| Wheat straw              | chamber              | PM_{2.5}| 2.2          | Hays et al. 2005    |
| Wood (Pine)              | wind tunnel          | PM_{10} | 0.19         | Turn et al. 1997    |
| Wood (Pine)              | field measurement    | PM_{2.5}| 0.76         | Zhang et al. 2012   |

The compounds employed for the analysis of WSOC occupied approximately 22% of entire compounds, which were equivalent to 7% of the weight of PM_{2.5}. In regard to each item employed for the analysis, the alkanoic acid appeared as 4.94% of the weight of PM_{2.5}, while the levoglucosan, di-carboxylic acid, benzene carboxylic acid and amino acids appeared with 2.13%, 0.16%, 0.02% and 0.02% of the weight of PM_{2.5}, respectively. Major chemical components contained in the alkanoic acid which manifested the highest content in WSOC appeared in the order of hexadecanoic acid > triacontanoic acid > oleic acid > tetradecanoic acid > linoleic acid > dehydroabietic acid. hexadecanoic acid exhibited higher content in alkanoic acid group and it occupied approximately 25.25% among entire alkanoic acid, while triacontanoic acid, oleic acid, tetradecanoic acid, linoleic acid and dehydroabietic acid appeared with respective occupancies of 8.20%, 7.16%, 6.95%, 6.36% and 6.25%; the six compounds occupied more than 60% of the entire 27 compounds. In regard to the comparison of specimens of woods with herbaceous plant, the content of octanoic acid, decanoic acid, dodecanoic acid and pentadecanoic acid appeared higher in specimens of woods than in herbaceous plant; the other compounds appeared with higher content in specimen of herbaceous plant. With regard to the classification of compounds according to respective characteristics, the average concentration of alkanoic acid in the soft specimens appeared as 110.60 mg/g-OC while the concentration of alkanoic acid in the hard specimens appeared as 57.88 mg/g-OC, signifying the concentration of alkanoic acid appeared increasing in accordance with decreasing density of specimen.
To trace the biomass materials of plants, wherein the suberic acid was detected only from specimens of woods while the adipic acid was detected only from the stalk of the herbaceous plant. In particular, soft specimens, suggesting lower emission from hard specimens than soft specimens. In regard to the classification of specimens into the hard woods.

The analyzed amino acid occurred in the order of succinic acid > glutaric acid > azelaic acid. Among alkanes (n-tridecane, n-tetradecane, n-pentadecane, n-hexadecane, etc.), the most abundantly contained in the WSOC appeared in the order of triacontanoic acid, which manifested the highest content in WSOC appeared in the order of tetradecanoic acid occupied approximately 0.16% of the weight of PM2.5. Major chemical components of benzene carboxylic acid, both the phthalic acid and methylphthalic acid were detected only from specimens of woods while the adipic acid was detected only from the stalk of the herbaceous plant; the other 6 compounds were not detected.

The yield of levoglucosan appeared as 1.96 mg/g for the soft specimen. This agrees with the results of previous studies reported the evoglucosan appeared with respective occupancies of 8.20%, 7.16%, 6.95%, 6.36%, 4.94% of the weight of PM2.5, while the levoglucosan, dihydroxyacetone, and dihydroxyacetone appeared as 0.52 mg/g from specimens of herbaceous plant, while the adipic acid, linoleic acid, and dehydroabietic acid appeared in the order of succinic acid > glutaric acid > azelaic acid. The ratio of levoglucosan to OC (evoglucosan/OC of hard specimen (109 –168 mg/g-OC) appeared higher than that of soft specimen (52–95 mg/g-OC) 

Figure 3. Composition ratio of PM2.5 mass by biomass burning of woods and agricultural byproducts.
Levoglucosan is created solely by the decomposition of cellulose and hemicellulose to be burnt at temperature over 300 °C [44,45]. Therefore, the levoglucosan is employed as one of organic molecular markers of PM$_{2.5}$ created from the biomass burning. To trace the biomass materials of burning by using the acceptance model, the ratio of levoglucosan to OC (levoglucosan/OC, mg/g-OC) is generally used [46–48] In the present study, the content of levoglucosan in WSOC appeared as the second largest one, which was corresponded to 2.11% of the weight of PM$_{2.5}$; the levoglucosan/OC appeared distributing in the range 26.99–157.29 mg/g-OC. With regard to the classification according to characteristics of emission represent the detailed characteristics of emitted materials which were varied according to inherent characteristics of woods (hard) and herbaceous plant (soft). In particular, the emission of amino acid compounds of benzene carboxylic acid, both the phthalic acid and methylphthalic acid were commonly detected however, the rest of 6 compounds were not detected. The analyzed amino acid was detected from all specimens. Benzene carboxylic acid and amino acids were not detected from specimens of herbaceous plant. In regard to the classification of specimens into the hard- and soft ones, it appeared as occupying 0.02% and 0.04% of the weight of PM$_{2.5}$; wherein the artificial burning of agricultural byproducts and spontaneously generated forest fire etc. are distinguished. The artificial burning of agricultural byproducts and spontaneously generated forest burning. To trace the biomass materials of burning by using the acceptance model, the ratio of levoglucosan to OC (levoglucosan/OC, mg/g-OC) is generally used [46–48] In the present study, the content of levoglucosan in WSOC appeared as the second largest one, which was corresponded to 2.11% of the weight of PM$_{2.5}$; the levoglucosan/OC appeared distributing in the range 26.99–157.29 mg/g-OC. With regard to the classification according to characteristics of compounds employed for the analysis, the average levoglucosan/OC of hard specimen appeared as approximately 100.24 mg/g, while it was in the range 32.67 mg/g-OC for the soft specimen. This agrees with the results of previous studies reported the yield of levoglucosan/OC of hard specimen (109–168 mg/g-OC) appeared higher than that of soft specimen (52–95 mg/g-OC) [49].

Di-carboxylic acid occupied approximately 0.16% of the weight of PM$_{2.5}$ for both specimens of woods and herbaceous plants. The percentage of contents of analyzed di-carboxylic acid appeared in the following order of succinic acid > glutaric acid > azelaic acid, wherein the suberic acid was detected only from specimens of woods while the adipic acid was detected only from the stalk of woods. Pimelic acid was not detected from all specimens. Benzene carboxylic acid and amino acids appeared as occupying 0.02% and 0.04% of the weight of PM$_{2.5}$, respectively. From the analyzed 8 compounds of benzene carboxylic acid, both the phthalic acid and methylphthalic acid were commonly detected however, the rest of 6 compounds were not detected. The analyzed amino acid was detected with the average 0.48 mg/g-OC emitted from specimens of woods and 1.25 mg/g-OC from specimens of herbaceous plant. In regard to the classification of specimens into the hard- and soft ones, it appeared as 0.52 mg/g-OC from the hard specimens, while it was 0.81 mg/g-OC from the soft specimens, suggesting lower emission from hard specimens than soft specimens. In particular, the emission of amino acid...
from rice straw appeared as 1.96 mg/g-OC, which was approximately 3.5 times higher than that from hard specimens and twice as much as that from soft specimens.

The characteristics of chemical components in PM$_{2.5}$, which is created from the burning of woods and agricultural byproducts, were examined together with characteristics of emitted materials which were varied according to inherent characteristics of woods (hard) and herbaceous plant (soft). In short, the ratio of OC/EC of soft specimens appeared higher than that of hard specimens, while the PAHs of woods appeared higher than that of herbaceous plant. In addition, for the case of alkane, the compounds of analysis of C$_{11}$–C$_{29}$ exhibited higher level in specimens of woods than that in specimens of herbaceous plant, whereas the compounds of analysis in the range C$_{30}$–C$_{40}$, they manifested characteristics of higher level in specimens of herbaceous plant than in specimens of woods. Hard specimen of alkanoic acid appeared higher than that of soft specimen, while the yield of levoglucosan/OC appeared higher in hard specimens than that of soft specimens. The above characteristics of emission represent the detailed organic molecular markers of the biomass burning. The results obtained from the present study are expected to be presenting organic molecular markers of PM$_{2.5}$, wherein the artificial burning of agricultural byproducts and spontaneously generated forest fire, etc. are distinguished.

3.2. Ambient Concentrations

The seasonal PM$_{2.5}$ was collected to determine the contribution of causes to resulting PM$_{2.5}$ in the subject area of the present study. A total of 160 chemical components, comprising PM$_{2.5}$, OC, EC, 6 ionic components, 23 PAHs, 16 kinds of hopanes and steranes, 33 kinds of alkanes, 6 kinds of cyclo-alkanes, 33 kinds of alkanoic acids, 8 kinds of benzene carboxylic acids, 8 kinds of alkanoic diacids, levoglucosan, cholesterol and 20 kinds of the other chemical components, were analyzed (Table 4).

Annual average concentration of PM$_{2.5}$ in the subject area of the present study was 25.44 µg/m$^3$, whereas those in residential area and on roads were 19.07 µg/m$^3$ and 31.81 µg/m$^3$, respectively. Seasonal PM$_{2.5}$ in the subject area appeared as in the following order of summer (22.71 µg/m$^3$) > autumn (18.59 µg/m$^3$) ≥ winter (18.50 µg/m$^3$) > spring (16.47 µg/m$^3$), whereas it appeared on roads as in the following order of winter (62.79 µg/m$^3$) > spring (29.27 µg/m$^3$) > summer (23.17 µg/m$^3$) > autumn (12.02 µg/m$^3$).

Annual average concentration of OC and EC in the subject area of the present study appeared as 6.37 µg/m$^3$ and 1.50 µg/m$^3$, respectively. The annual average concentration of OC and EC in the residential area were 4.99 µg/m$^3$ and 1.10 µg/m$^3$, respectively, whereas those on roads appeared as 7.75 µg/m$^3$ and 1.91 µg/m$^3$. In general, EC refers to the primary particles emitted from the biomass burning, coal and diesel oil, etc. [7,9]. On the contrary, OC is classified into the primary organic carbon (POC) and secondary organic carbon (SOC) according to respective processes of creation [8]. Thereby, the ratio of OC to EC as well as EC tracer method can be employed for the prediction of the ratio of SOC in OC [50]. According to the EC tracer method, the ratio of OC/EC over 2.5 is generally known that it contributes largely to the creation of the secondary OC. The ratio of annual average OC/EC appeared in residential area as 5.35, while it appeared in roads as 4.24; this suggests comparatively higher content of SOC therein.
| Compounds                              | Unit | Site 1 (Residential Area) | Site 2 (Roadside Area) |
|----------------------------------------|------|---------------------------|------------------------|
|                                        |      | Spring       | Summer       | Fall        | Winter      | Spring       | Summer       | Fall        | Winter      |
| PM$_{2.5}$                             | ug/m$^3$ | 16.47 ± 0.75 | 22.71 ± 0.47 | 18.59 ± 1.79 | 18.50 ± 1.80 | 29.27 ± 3.83 | 23.17 ± 1.01 | 12.02 ± 1.26 | 62.79 ± 0.96 |
| OC                                     | ug/m$^3$ | 4.81          | 6.22          | 6.30         | 2.65        | 10.53        | 5.42         | 3.58        | 11.46       |
| EC                                     | ug/m$^3$ | 0.76          | 1.94          | 1.32         | 0.38        | 2.36         | 1.78         | 1.99        | 1.50        |
| K$^+$                                  | ug/m$^3$ | 0.07          | 0.09          | 0.20         | 0.17        | 0.19         | 0.09         | 0.10        | 0.47        |
| SO$_{4}^{2-}$                          | ug/m$^3$ | 3.23          | 10.11         | 3.14         | 5.08        | 5.42         | 10.74        | 2.62        | 11.81       |
| NO$_3^-$                               | ug/m$^3$ | 4.30          | 0.11          | 2.99         | 3.96        | 2.53         | 0.08         | 0.67        | 24.69       |
| NH$_4^+$                               | ug/m$^3$ | 2.10          | 3.51          | 1.99         | 2.92        | 2.59         | 3.54         | 1.05        | 10.02       |
| Cl$^-$                                 | ug/m$^3$ | 0.04          | 0.00          | 0.03         | 0.45        | 0.03         | 0.00         | 0.01        | 1.11        |
| Na$^+$                                 | ug/m$^3$ | 0.06          | 0.04          | 0.06         | 0.26        | 0.08         | 0.05         | 0.14        | 0.17        |
| Mg$^{2+}$                              | ug/m$^3$ | 0.01          | 0.01          | 0.02         | 0.05        | 0.03         | 0.02         | 0.03        | 0.08        |
| Ca$^{2+}$                              | ug/m$^3$ | 0.05          | 0.01          | 0.03         | 0.03        | 0.12         | 0.03         | 0.05        | 0.13        |
| levoglucosan                           | ng/m$^3$ | 239           | 197           | 1173         | 722         | 985          | 76           | 134         | 2834        |
| Cholesterol                            | ng/m$^3$ | 0.00          | 0.79          | 0.00         | 0.00        | 4.24         | 0.00         | 0.00        | 11.19       |
| ΣPAHs                                  | ng/m$^3$ | 8.31          | 5.32          | 27.97        | 43.22       | 45.40        | 5.33         | 7.71        | 170.72      |
| ΣHopanes Z and Sterane                 | ng/m$^3$ | 0.45          | 0.26          | 0.92         | 1.00        | 4.00         | 0.80         | 0.76        | 6.14        |
| ΣAlkanes                               | ng/m$^3$ | 81            | 69            | 241          | 147         | 456          | 66           | 65          | 841         |
| ΣCyclo-alkanes                         | ng/m$^3$ | ND 1)         | ND            | ND           | ND          | ND           | ND           | ND          | 3.79        |
| Σalkanoic acids                        | ng/m$^3$ | 321           | 223           | 644          | 365         | 1261         | 244          | 256         | 2149        |
| Σbenzene carboxylic acids              | ng/m$^3$ | 103           | 142           | 223          | 243         | 435          | 88           | 80          | 812         |
| ΣAlkanoic Diacids                      | ng/m$^3$ | 276           | 188           | 200          | 201         | 633          | 105          | 120         | 699         |
| ΣOther acids                           | ng/m$^3$ | 599           | 1930          | 976          | 212         | 4281         | 1568         | 315         | 1497        |

1) Not detected.
The compounds, analyzed as an organic indicator of WIOC, were 56 compounds of PAHs and alkanes; the percentage of PAHs and alkanes to weight of PM$_{2.5}$ were 0.15% and 0.97%, respectively. PAHs are emitted through incomplete combustion of fossil fuels and biomass. In the present study, the annual average concentration of PAHs in residential area appeared as approximately 84.82 ng/m$^3$, while it appeared on roads as 229.16 ng/m$^3$ showing higher level of annual average concentration than that appeared in the residential area. This was estimated that it would be attributable to PAHs created from the combustion of fuels of motor vehicles that affected the area of roads. The detected seasonal concentration of PAHs commonly marked the highest level in both residential area and on roads in wintertime (residential area 43.22 ng/m$^3$, roads 170.72 ng/m$^3$), whereas it marked the lowest level in summertime (residential area 5.32 ng/m$^3$, roads 5.33 ng/m$^3$). According to previously conducted studies, the higher concentration of PAHs in wintertime was reported to be associated with the effect of phenomenon of cold ignition of vehicles; while the lower concentration of PAHs has been reported that it would be attributable to the effect of photochemical decomposition [51,52]. The varied seasonal concentration of PAHs, identified in the present study, was also estimated to be affected by effects of cold ignition of vehicles in wintertime and photochemical decomposition in summertime, as it was reported in previously conducted studies.

The sum of annual average concentration of alkanes appeared as 538 ng/m$^3$ in residential area and 1428 ng/m$^3$ on roads; the seasonal concentration thereof tended to show behaviors similar to seasonal variations of PAHs however the concentration in residential area appeared higher in summertime than that in wintertime. The sum of concentration of alkanes, observed in wintertime, appeared as 147 ng/m$^3$ in residential area and 841 ng/m$^3$ on roads; it appeared in residential area and on roads as 69 ng/m$^3$ and 66 ng/m$^3$, respectively, in summertime. Carbon Preference Index (CPI) signifies the ratio of concentrations of odd numbered alkanes to even numbered alkanes, wherein the C$_{max}$ is defined as the number of carbons of detected peak concentration, and it represents the input of anthropogenic sources [53]. The value of CPI close to 1 in the acceptance model implies the artificial emission of fossil fuels whereas the value over 2.0 represents the alkanes originated from biomass [53–55].

Hopanes and steranes are the ones of organic indicators of PM$_{2.5}$ which are mainly created from fossil fuels. Therefore, the hopanes and steranes, contained in the exhaust from vehicles or thermoelectric power plants wherein fossil fuels are used, are detected comparatively in higher level [10,56,57]. A total of 16 compounds of hopanes and steranes substances including 17α(H)-21,22,29,30-trinorhopane, 17β(H)-21α(H)-30-norhopane and 17α(H)-21β(H)-hopane were analyzed as an ingredient of organic indicators of fossil fuels. Annual average concentration hopanes and steranes appeared in the subject area as 0.66 ng/m$^3$ in the residential area and 2.93 ng/m$^3$ on roads; the roads appeared with higher level of concentration.

Levoglucosan is a substance of organic indicator resulted from the biomass burning. Annual average concentration of levoglucosan in the subject area of the present study appeared as 582.75 ng/m$^3$ (residential area) and 1007.25 ng/m$^3$ (roads), respectively. With regard to the seasonal concentrations of levoglucosan, the highest concentration of 1173 ng/m$^3$ appeared in residential area in autumn, while the highest concentration of 2834 ng/m$^3$ appeared on roads in wintertime. However, the ratio of levoglucosan/OC, employed for the acceptance model, appeared higher in wintertime regardless of the area of residence or roads; the ratio of levoglucosan/OC in wintertime appeared as 272.45 mg/g (residential area) and 247.29 mg/g (on roads), respectively. Further, the ratio of K$^+/EC$, the one of indicator chemical components of biomass burning, also appeared with the highest level of 0.45 (annual average 0.18) in the residential area and 0.51 (annual average 0.12) on roads in wintertime. Therefore, the biomass burning in the subject area of the present study was identified to be increasing mainly in wintertime. The cholesterol, one of WSOC, is the one of organic indicator chemical components resulted from the burning of meats [24]. Previous study had employed the ratio of cholesterol to OC for the CMB model as an indicator material of burning of meats; the ratio of cholesterol/OC used in the previously conducted study was 0.0010 [58]. The annual average concentration of cholesterol appeared as 0.20 ng/m$^3$ in residential area and 3.86 ng/m$^3$ on roads, respectively, in the present study. The ratio
of cholesterol/OC appeared commonly below 0.0000 in all four seasons in the residential area, whereas it appeared on roads as 0.0004 in spring and 0.0010 in wintertime. In regard to the annual average concentration and seasonal concentration, the creation of PM$_{2.5}$ resulted from the burning of meats appeared higher on roads. This was attributed to the effects of restaurants placed around roads.

### 3.3. Source Apportionment Model

Two well-known source apportionment models (CMB and positive matrix factorization (PMF)) have been used for several decades to identify the complex sources of carbonaceous aerosols. CMB is based on an effective variance least squares (EVLS) multilinear regression method. PMF is an explicit point-by-point weighted least squares factor analysis method imposed with non-negativity constraints. Although CMB does not require a minimum set of input data, the selection of the source profile controls the model result sensitivities. The results obtained from the CMB model using the source profiles obtained in this study are presented in Table 5 and Figure 5. The data, employed for the analysis conducted in the CMB model, were comprised of a total of 160 compounds including PM$_{2.5}$, OC, EC, PAHs and hopanes and steranes, etc.; the analysis of organic molecular markers of the biomass burning used the results of study presented in ‘Section 3.1’. As illustrated in the figure, the origins of PM$_{2.5}$ in the subject area of the present study appeared as in the following order: secondarily created ionic substances (54.10%) > contribution to the secondary created particulate matters and long-distance pollutants (20.02%) > biomass burning from agricultural crop residues (8.96%) and forest tree types (1.56%) (10.53%) > emission from vehicles of gasoline engine (4.79%) > Burning of meats or others in restaurants (2.65%). With regard to the comparison of residential area with the area on roads, the secondarily created ionic substances and the secondarily created particulate matters and long-distance pollutants, which occupy most origins of PM$_{2.5}$, appeared with similar rates over 72% commonly in residential area and on roads. For the case of the biomass burning, it appeared higher in the residential area (14.4%) than on roads (8.2%) due to relatively higher impacts from the open-burning of agricultural crop residues; the emission from vehicles of gasoline engine and from the burning in restaurants appeared higher on roads than those in the residential area. The rest of the burning of natural gas, combustion in coal burning thermal power plants, and water soluble ionic substances (sea-salt particulates), etc. were commonly identified as exhibiting no significant differences between residential area and on roads. In this study, there are still limitation about secondary mass from primary in the CMB result as shown in Table 5. The identified sources of secondary ions, SOA and oxidized trace elements may include mass from the primary sources such as biomass burning and car emission.

| Overall Avg | Residential Area | Roadside Area |
|---|---|---|
| PM$_{2.5}$ mass | 27.54 | 100.00 | 20.769 | 100.00 | 34.306 | 100.00 |
| Biomass burning (agricultural crop residues) | 2.47 | 8.96 | 2.52 | 12.13 | 2.42 | 7.05 |
| Biomass burning (forest tree types) | 0.43 | 1.56 | 0.47 | 2.24 | 0.40 | 1.15 |
| Vegetative detritus | 0.79 | 2.87 | 0.664 | 3.20 | 0.916 | 2.67 |
| Natural gas combustion | 0.14 | 0.49 | 0.111 | 0.54 | 0.160 | 0.46 |
| Diesel car emission | 0.52 | 1.87 | 0.422 | 2.03 | 0.609 | 1.77 |
| Gasoline car emission | 1.32 | 4.79 | 0.726 | 3.49 | 1.914 | 5.58 |
| Meat cooking emission | 0.73 | 2.65 | 0.244 | 1.18 | 1.217 | 3.55 |
| Coal combustion | 0.40 | 1.44 | 0.325 | 1.57 | 0.469 | 1.37 |
| Secondary ions | 14.90 | 54.10 | 10.856 | 52.27 | 18.938 | 55.20 |
| Water soluble salts | 0.36 | 1.32 | 0.286 | 1.38 | 0.441 | 1.28 |
| SOA, oxidized trace elements, and/or long range transfer | 5.51 | 20.02 | 4.149 | 19.98 | 6.877 | 20.05 |
4. Conclusions

In the present study, the experimental burning of ten types of biomass were carried out to determine the organic chemical speciation using the biomass burning chamber. The results of the profile analyses were used for the identification of sources of PM$_{2.5}$ in residential area and on roads by exploiting the CMB model. The organic molecular markers for the biomass burning were identified as they were varying according to specimens of forest tree types and agricultural byproducts, depending upon the hard and soft characteristics of specimens. The chemical speciation of organic molecular markers, to be varying according to respective characteristics of cultivation of burning materials, were estimated based on results of the present study. The result suggests that chemical profiles of organic molecular markers are needed according to respective crops to be cultivated and agricultural characteristics in countries to determine the organic molecular markers corresponding to biomass burning. The sources of PM$_{2.5}$ were determined based on the CMB model wherein the organic molecular markers of biomass burning, employed for the present study, were included. Major sources of PM$_{2.5}$ in the subject area of the present study appeared as sources of biomass burning, the secondary ions, secondary particulate matters, which is including long-distance transport, wherein the three sources occupied most over 84% of entire PM$_{2.5}$. In regard to the subject area distinguished into residential area and on roads, the portion of the biomass burning appeared higher in residential area than on roads. In the present study, the organic molecular markers for the biomass burning including major woods and agricultural byproducts in Korea were presented and the origins of PM$_{2.5}$ were identified via employing the CMB model exploiting data above.

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Abbreviations

The following abbreviations are used in this manuscript:

| Abbreviation | Meaning |
|--------------|---------|
| ALA          | Alkanoic acids |
| BCA          | benzene carboxylic acid |
| DCA          | di-carboxylic acid |
| Glu          | glutamic acid |
| Ser          | serine |
| His          | histidine |
| Gly | glycine          |
| Thr | threonine       |
| Arg | arginine        |
| Ala | alanine         |
| Tyr | tyrosine        |
| Cys | cystine         |
| Val | valine          |
| Met | methionine      |
| Phe | phenylalanine   |
| Iso | isoleucine      |
| Leu | leucine         |
| Lys | lysine          |
| Phen| phenanthrene    |
| Anth| anthracene      |
| Fluo| fluoranthene    |
| Acep| acenaphthylene  |
| Pyre| pyrene          |
| Bgfa| benzo(ghi)fluoranthene |
| Cpcp| cyclopenta(cd)pyrene |
| Baan| benz(a)anthracene |
| Chry| chrysene        |
| 1mch| 1-methylchrysene |
| Rete| retene          |
| Bbfl| benzo(b)fluoranthene |
| Bkfl| benzo(k)fluoranthene |
| Bjfl| benzo(j)fluoranthene |
| Bepy| benzo(e)pyrene  |
| Bapy| benzo(a)pyrene  |
| Pery| perylene        |
| Inpy| indeno(1,2,3-cd)pyrene |
| Bgpe| benzo(g,h,i)perylene |
| Dbaa| dibenz(a,h)anthracene |
| Pice| picene          |
| Coro| coronene        |
| Dbap| dibenzo(a,e)pyrene |
| C\textsubscript{11} | n-undecane |
| C\textsubscript{12} | n-dodecane |
| C\textsubscript{13} | n-tridecane |
| C\textsubscript{14} | n-tetradecane |
| C\textsubscript{15} | n-pentadecane |
| C\textsubscript{16} | n-hexadecane |
| C\textsubscript{18i} | norpristane |
| C\textsubscript{17} | n-heptadecane |
| C\textsubscript{19} | pristane |
| C\textsubscript{18} | n-octadecane |
| C\textsubscript{20a} | phytane |
| C\textsubscript{19} | n-nonadecane |
| C\textsubscript{20} | n-eicosane |
| C\textsubscript{21} | n-heneicosane |
| C\textsubscript{22} | n-docosane |
| C\textsubscript{23} | n-tricosane |
| C\textsubscript{24} | n-tetracosane |
| C\textsubscript{25} | n-pentacosane |
| C\textsubscript{26} | n-hexacosane |
C_{27} \quad \text{n-heptacosane}
C_{28} \quad \text{n-octacosane}
C_{29} \quad \text{nonacosane}
C_{30} \quad \text{triacontane}
C_{31} \quad \text{hentriacontane}
C_{32} \quad \text{dotriacontane}
C_{33} \quad \text{tritriacontane}
C_{34} \quad \text{tetracontane}
C_{35} \quad \text{pentriacontane}
C_{36} \quad \text{hexatriacontane}
C_{37} \quad \text{heptatriacontane}
C_{38} \quad \text{octatriacontane}
C_{39} \quad \text{nonacontane}
C_{40} \quad \text{tetracontane}
Octa \quad \text{octanoic acid}
Deca \quad \text{decanoic acid}
Deda \quad \text{dodecanoic acid}
Deda \quad \text{dodecanoic acid}
Teta \quad \text{tetradecanoic acid}
Pena \quad \text{pentadecanoic acid}
Hexa \quad \text{hexadecanoic acid}
Hepa \quad \text{heptadecanoic acid}
Ocda \quad \text{octadecanoic acid}
Noda \quad \text{nonadecanoic acid}
Pina \quad \text{pinonic acid}
Pala \quad \text{palmitoleic acid}
Olea \quad \text{oleic acid}
Lina \quad \text{linoleic acid}
Lnna \quad \text{linolenic acid}
Eica \quad \text{eicosanoic acid}
Hena \quad \text{heneicosanoic acid}
Doca \quad \text{docosanoic acid}
Trca \quad \text{tricosanoic acid}
Teca \quad \text{tetracosanoic acid}
Peca \quad \text{pentacosanoic acid}
Hxca \quad \text{hexacosanoic acid}
Hpca \quad \text{heptacosanoic acid}
Otca \quad \text{octacosanoic acid}
Nnca \quad \text{nonacosanoic acid}
Tnca \quad \text{triacontanoic acid}
Dhaa \quad \text{dehydroabietic acid}
7oaa \quad \text{7-oxodehydroabietic acid}
Phaa \quad \text{phthalic acid}
Ipha \quad \text{isophthalic acid}
Tpha \quad \text{terephthalic acid}
124B \quad 1,2,4-benzenetricarboxylic acid
123B \quad 1,2,3-benzenetricarboxylic acid
135B \quad 1,3,5-benzenetricarboxylic acid
1245B \quad 1,2,4,5-benzenetetracarboxylic acid
Mepa \quad \text{methylphthalic acid}
Suca \quad \text{succinic acid}
Glua \quad \text{glutaric acid}
Adia \quad \text{adipic acid}
Pima \quad \text{pimelic acid}
Suba \quad \text{suberic acid}
Azea azelaic acid
Seba sebacic acid
Levo levoglucosan

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