Abstract: Atmospheric particles with an aerodynamic diameter less than or equal to 2.5 micrometers (PM$_{2.5}$) were collected at two sites located in the urban area of the city of Cuernavaca (Morelos) during a season when a large number of forest fires occurred. Three dicarboxylic acids (malonic, glutaric and succinic) and levoglucosan were analyzed by liquid chromatography coupled with mass spectrometry (ESI-Q-TOF) and soluble potassium (K$^+$) was analyzed by ion chromatography. The concentration of PM$_{2.5}$ increased on the days when the highest number of forest fires occurred. A strong correlation was observed between levoglucosan and K$^+$, confirming the hypothesis that both are tracers of biomass burning ($r = 0.57$, $p < 0.05$). Levoglucosan (average 367.6 ng m$^{-3}$, Site 2) was the most abundant compound, followed by succinic acid (average 101.7 ng m$^{-3}$, Site 2), glutaric acid (average 63.2 ng m$^{-3}$, Site 2), and malonic acid (average 46.9 ng m$^{-3}$, Site 2), respectively. The ratio of C$_3$/C$_4$ concentrations ranged from 0.5 to 1.2, with an average of 0.8, which suggests great photochemical activity in the Cuernavaca atmosphere. The ratio of K$^+$/levoglucosan concentrations (0.44) indicates that open fires are the main source of these tracers. The positive correlations between PM$_{2.5}$ and levoglucosan and succinic and malonic acids suggest that such compounds are contributing to secondary organic aerosol particle formation.

Keywords: forest fires; levoglucosan; dicarboxylic acids; open burning

1. Introduction

Biomass burning is a major source of particulate matter in ambient air, with the particles consisting of hundreds of organic and inorganic compounds, causing significant impacts on regional to global air quality [1], human health [2] and climate [3]. The composition of the atmospheric particles depends on diverse factors, such as the original source, the amount of emission, the meteorological conditions and
the topography of the area in which generation occurs [4,5]. Due to the complex chemical composition of the emissions caused by the burning of biomass, it is not easy to find exact tracers.

Water-soluble organic compounds (WSOC) constitute an important fraction of atmospheric organic matter [6], representing between 10% and 90% of organic carbon content in atmosphere aerosols, depending on location and season. Primary organic aerosols (POA) and secondary organic aerosols (SOA) are ubiquitous in the atmosphere, and their proportion will largely depend on emission factors and prevailing weather conditions [7]. In the pyrolysis of plant products rich in cellulose and hemicellulose, a large number of low molecular weight (LMW) polar compounds have been identified, such as anhydrosugars [8], sugar alcohols [9], primary sugars and oxalic acid (C2) [10], as well as several sugar derivatives [11]. These compounds are potentially important molecular markers when trying to determine the source of both anthropogenic and natural aerosols and elucidating the processes and pathways of organics in atmospheric aerosols [12]. The most commonly used organic tracer is levoglucosan, a sugar anhydride produced via pyrolysis of cellulose and hemicelluloses; it is a highly specific molecular marker for biomass burning [13,14].

Dicarboxylic acids are another important class of WSOC in the atmosphere. These are produced by primary sources, such as biomass burning and fossil fuel combustion [15,16], but the major portion results from photooxidation of organic precursors, so dicarboxylic acids are thus considered, in general, as secondary products [17]. The diacids significantly change the hygroscopicity of atmospheric aerosols, contributing directly to the earth’s radiation balance by scattering incoming solar radiation, as well as to the increase of cloud condensation nuclei [18,19]. For its part, water-soluble potassium (K+) has been used widely as an inorganic tracer for biomass burning [20,21].

In México, climatic factors such as drought, hurricanes, and the El Niño and La Niña phenomena impact directly and indirectly the forested areas of the country, generating conditions that favor the development of forest fires of different magnitude and severity. In recent years, these forest fires have manifested extreme behavior and high resistance to control. In the state of Morelos, the number of fires and the area affected are directly related to human activities and the behavior of hydrometeorological phenomena. Specifically, the behavior of drought, or the lack of relative humidity in the environment, together with the accumulation of dead vegetative material, contributes significantly to the generation of fires [22].

Despite the relevance of these types of studies, which allow for the evaluation of the impact that these compounds have on the behavior of climate change at the local and global level, in the Mexican Republic, there are few records of the concentration levels of some of these biomarkers [23,24]. Specifically, for the state of Morelos, there is no scientific study that has reported the concentration levels of these species.

The aim of the work presented here is to characterize the concentrations of combustion tracers in ambient air, such as levoglucosan, dicarboxylic acids and water-soluble potassium in the urban environment in Morelos, in 2016, between the months of February and August, the period in which the largest number of forest fires occur.

2. Materials and Methods

2.1. Sampling Sites

The city of Cuernavaca is located in the center of the Mexican Republic, 85 km from Mexico City. According to the last census, it has a population of 365,168 inhabitants [25] (Figure 1). Two sites were selected for sampling. The first one, downtown in the city (Centro, Site 1), is an area characterized by high vehicular and commercial activity. The second site is located north of the city, within the Autonomous University of the State of Morelos (Center of Chemical Research, CIQ for its acronym in Spanish, Site 2), and is surrounded by a variety of vegetation. The sampling sites were selected according to 40 CFR Part 58 Appendix A of the USEPA Code of Federal Regulations (CFR), taking into account the geographical characteristics, relevant anthropogenic activities and behavior of the meteorological variables [26].
2.2. Sampling of Airborne Particles

Sampling was done between February and August 2016. The particulate material was collected on fiberglass filters of 47 mm diameter and 2.0 µm pore size (Whatman, Darmstadt, Germany), which were conditioned in an oven at 550 °C for 30 min, and then transferred to a desiccator for 24 h. A low-volume (5.0 L min\(^{-1}\)) sampler (MiniVol™ TAS, Eugene, OR, USA) was used, equipped with a 2.5 µm impactor. Sampling was carried out for periods of 24 h (12:00 a.m.–12:00 p.m.). Gravimetric analysis was carried out under controlled room temperature and humidity (22 ± 3 °C, 40% ± 5%). Before weighing, the filters were stabilized for 24 h. Three blank filters per month were used as laboratory blanks. Each filter was weighed at least three times and the three readings had to agree within 5 micrograms to be accepted. The detection limit was calculated as 3 × SD of the mass change in the blank filters divided by the volume of the corresponding exposure time (24 h). The detection limit for the measurements was 0.92 mg m\(^{-3}\). The mass determination of PM\(_{2.5}\) was performed by weighing the filters before and after the collection period with a 0.1 µg sensitivity microbalance (Citizen CX-220™, Parwanoo, India). The concentration of PM\(_{2.5}\) in the atmosphere in mg m\(^{-3}\) was obtained by dividing the mass by the volume of filtered air, adjusted to conditions of standard temperature and pressure (25 °C and 760 mm Hg).

2.3. Meteorological Parameters and Criteria Pollutants

Simultaneously, meteorological parameters were monitored at both sites (temperature, relative humidity, solar radiation, wind speed and wind direction). Additionally, only at Site 1, criteria pollutant data were obtained (O\(_3\), SO\(_2\), NO\(_x\) and CO) (Table 1).

Table 1. Meteorological conditions and criteria pollutants during the sampling period.

| Meteorological Conditions and Criteria Pollutants | Average | SD | Minimum | Maximum |
|--------------------------------------------------|---------|----|---------|---------|
| Wind speed (m s\(^{-1}\))                        | 5.5     | 0.8| 4.0     | 7.0     |
| T °C                                             | 23      | 2  | 20      | 27      |
| % RH                                             | 48      | 15 | 17      | 72      |
| Radiation (W m\(^{-2}\))                        | 272     | 45 | 167     | 354     |
| SO\(_2\) (ppm)                                   | 0.0013  | 0.0007 | 0.0004 | 0.0030 |
| NO\(_x\) (ppm)                                   | 0.044   | 0.031 | 0.014  | 0.122   |
| CO (ppm)                                         | 0.585   | 0.170 | 0.224  | 0.778   |
| O\(_3\) (ppm)                                    | 0.024   | 0.009 | 0.010  | 0.049   |

SD: Standard deviation.
2.4. Extraction of Water-Soluble Organic Compounds

The sampled filters were placed in polypropylene tubes, and then 8.0 mL of Milli-Q water was added to each tube and extracted in an ultrasound bath (Branson 3210) for 1.0 h. The Erlenmeyer flasks in which the filters were introduced were fitted with cooled condensers with water at 10 °C; then the extracts were filtered through nylon membranes with a pore size 0.45 µm. Once the extracts were filtered, they were transferred to injection vials and stored at approximately 4 °C, until chromatographic analysis.

2.5. Chromatographic Analysis

The analysis of the WSOC was carried out by using Ultra-High-Performance Liquid Chromatography (UHPLC) in an Agilent 1290 Infinity LC System, coupled to a quadrupole-time-of-flight (Agilent Q-TOF 6545 mass spectrometer), equipped with an electrospray ionization source (ESI). The ESI-MS conditions were optimized by injection of single standard at a concentration of 100 ng mL\(^{-1}\) of four compounds (levoglucosan and glutaric, malonic and succinic acids), in both positive and negative ionization mode. No signal was recorded in positive mode. Highly abundant analytes signals were detected in negative mode. Table 2 shows optimal instrumental operating conditions.

Table 2. Summary of source parameters for negative ion mode method.

| Parameter                  | Value            |
|----------------------------|------------------|
| Tune                       | 50–250 m/z       |
| Drying gas temperature     | 190 °C           |
| Drying gas flow            | 9.0 L/min        |
| Nebulizer pressure          | 29 psi           |
| Capillary voltage          | 4000 V           |
| Fragmentor                 | 110 V            |
| Collision RF Vpp           | 150 V            |
| Acq mass range             | 100–1100 m/z     |
| Acq rate                   | 2 spectra/s      |

For the separation of compounds, a Zorbax Rapid Resolution High Definition SB-C18 column with a 2.1 mm internal diameter × 50 mm and a particle pore size of 1.8 µm was used. The mobile phase was a solution of NH\(_4\)OH 13 mM in methanol:water (85:15), which was used in isocratic mode. The identification of the compounds was carried out by the retention time and the molecular ion (Table 3).

Table 3. Selected parameters for the identification of dicarboxylic acids and levoglucosan by UHPLC.

| Compound   | Retention Time (min) | Mass (m/z)   |
|------------|----------------------|--------------|
| Malonic    | 1.3                  | 103.0036     |
| Succinic   | 1.9                  | 117.0194     |
| Glutaric   | 2.4                  | 131.035      |
| Levoglucosan | 3.1                | 161.0457     |

Meanwhile the analysis of soluble potassium (K\(^+\)) was determined by ion chromatography (IC, Metrohm model 861 Advanced Compact with conductivity detector), without chemical suppression in a Metrosep C\(_2\) 150 (Metrohm) column; the mobile phase was a solution of tartaric–dipicolinic acid (4.0:0.75 mM) at a flow rate of 1 mL min\(^{-1}\). The injection volume was 50 µL.

Calibrations for all studied compounds were based on serial dilutions from a stock solution made by dissolving individual compounds in solid form. Each calibration graph was made with five concentration points. The concentration range for levoglucosan and carboxylic acids was between 50 and 5000 ng mL\(^{-1}\), while for K\(^+\), this was between 50 and 1000 ng mL\(^{-1}\).
2.6. Quality Control of the Analytical Methods

To exclude the presence of the compounds of interest in the materials and reagents used, laboratory targets were done once a week. The extraction efficiency was determined by enriching filters with a mixture of the compounds studied at a concentration of 100 ppb for levoglucosan, malonic acid, succinic acid and glutaric acid and 500 ppb for K⁺. The enriched filters were extracted in the same way as the samples; the recovery percentages ranged from 80% to 85%. Furthermore, from the linear regression data, the detection limit of the method (LD) and quantification (LC) were determined, as well as the correlation coefficient (R) according to Miller and Miller (2002) [27] (Table 4).

| Compound     | LD (ng m⁻³) | LC (ng m⁻³) | R    |
|--------------|-------------|-------------|------|
| Levoglucosan | 51.3        | 171.1       | 0.9997|
| Malonic acid | 21.8        | 72.5        | 0.9945|
| Succinic acid| 45.7        | 152.4       | 0.9763|
| Glutaric acid| 9.1         | 30.4        | 0.9992|
| K⁺          | 0.5         | 1.2         | 0.9988|

LD: limit of detection. LC: limit of quantification.

2.7. Wind Trajectories

To determine the behavior of winds in the study area, HYSPLIT4 model trajectories, obtained from the NOAA (National Oceanic and Atmospheric Administration), were used [28]. During the study period, two patterns were observed with respect to the direction of the winds. The first occurred between February and April; in these months, the winds came mainly from the west–southwest. During the second period, from May to July, they came mainly from the east–southeast (Figure 2).
3. Results and Discussion

3.1. Concentrations of PM$_{2.5}$

In total, 35 samples were taken at each site, and the results revealed that the average concentration of PM$_{2.5}$ was 22 µg m$^{-3}$ for Site 1 (CENTRO) and 16 µg m$^{-3}$ for Site 2 (CIQ). The behavior of the PM$_{2.5}$ concentration was evaluated by time series (Figure 3). The results indicate some similarity, which is probably associated with common sources influencing both sites. The highest concentration of PM$_{2.5}$ was observed in February and between April and May, which is consistent with the forest fires that occurred in this period (Figure 4). According to official data, 52 fires occurred in February, 50 in March, 59 in April and 21 in May. This last month (May) is when the rains start, which allowed for the natural abatement of the fires and therefore the decrease in the concentration of PM$_{2.5}$ [22].
which allowed for the natural abatement of the fires and therefore the decrease in the concentration of PM$_{2.5}$ [22].

3.2. Molecular Tracers Associated with Airborne Particles

Table 5 summarizes the concentrations of levoglucosan and succinic, glutaric and malonic acids associated with PM$_{2.5}$ at both sampled sites in Cuernavaca and their average values with standard deviations, as well as maximum and minimum values.

Table 5. Mean concentration and range of the selected molecular markers during study period (ng m$^{-3}$).

|         | Centro | Average | SD   | Minimum | Maximum |
|---------|--------|---------|------|---------|---------|
| Levoglucosan | 354    | 127.4   | 140.9| 528.3   |         |
| Glutaric acid | 60.1   | 31      | 25.7 | 149.4   |         |
| Malonic acid  | 41     | 15.5    | 22.6 | 73.3    |         |
| Succinic acid | 77     | 34.6    | 48.4 | 149     |         |
| CIQ          |        |         |      |         |         |
| Levoglucosan | 367.6  | 57.6    | 86.8 | 676.2   |         |
| Glutaric acid | 63.2   | 21.7    | 28.3 | 159     |         |
| Malonic acid  | 46.9   | 11.5    | 24.7 | 94      |         |
| Succinic acid | 101.7  | 46.2    | 58.7 | 138.5   |         |

SD: standard deviation.

3.2.1. Levoglucosan

Levoglucosan was the compound with the highest concentration at both sites. At the CIQ site, the average concentration was slightly higher (367.6 ng m$^{-3}$, ±57.6), suggesting similar sources during the study period. Levoglucosan is the most abundant anhydrosugar reported in urban areas, due mainly to the burning of biomass [29]. Meanwhile, low concentrations found in summer could be attributed to the absence of residential heating in the warm season and better atmospheric conditions that favor atmospheric dispersion of pollutants. For its part, other minor sources such as emissions from fires for land clearance and/or accidental fires could be possible sources of levoglucosan in summer [30]. In this sense, it is important to highlight that, in the state of Morelos, about 182 forest fires occurred during the study period, which probably justifies the high concentrations of levoglucosan. Moreover, in some way, the presence of levoglucosan at this site probably indicates the transport of air masses from other regions of the state, specifically east and east-southeast, considering the behavior of wind trajectories, during the study period [28].
3.2.2. Dicarboxylic Acids

The concentration of some organic acids was also determined. At both sites, the most abundant compound was succinic acid (C$_4$), followed by glutaric acid (C$_5$) and malonic acid (C$_3$). Again, it is observed that the CIQ site presents slightly higher concentrations than the Centro site. When evaluating the behavior of the concentrations, it is observed that the maximum values were presented in the period (April–May) in which the greatest number of fires were registered, which is congruent with the observed behavior of the concentration of PM$_{2.5}$ and Levoglucosan.

The total average concentration of organic acids (C$_3$, C$_4$ and C$_5$) was 178.1 ng m$^{-3}$ at the Centro site and 211.8 ng m$^{-3}$ at the CIQ site. The excess concentration of succinic acid over malonic acid indicates that emissions can come from burning biomass, fossil fuel combustion and vehicular emissions [31,32]. Kawamura and Ikushima (1993) indicate that malonic acid is partly produced from the incomplete combustion of fossil fuels and biomass burning, but is mainly due to photochemical oxidation of succinic acid in the atmosphere [15]. On the other hand, Kawamura et al. (1996a) proposed that succinic acid can also be generated via the photo-oxidation of unsaturated fatty acids from terrestrial higher plants and domestic cooking [33].

Moreover, Kawamura and Sakaguchi (1999) proposed that the C$_3$/C$_4$ ratio is a good indicator to determine if the presence of dicarboxylic acids in the atmosphere corresponds to primary sources or oxidation processes [31]. Kawamura and Kaplan (1987) reported that lower C$_3$/C$_4$ ratios (0.25–0.44) correspond mainly to vehicular emissions, while values above that correspond to oxidation processes in the atmosphere [16]. The C$_3$/C$_4$ ratio obtained in this study, ranging from 0.5 to 1.2, with an average of 0.8, suggests that, in the urban area of Cuernavaca, photochemical processes regulate, to a large extent, the presence of the dicarboxylic acids studied.

3.2.3. Comparisons of the Observed Concentration for Levoglucosan and Dicarboxylic Acids with Other Studies

These comparisons should be analyzed with caution, since the results were obtained with different analytical methodologies and under different environmental conditions.

The average concentration of levoglucosan was lower than those reported in samples collected in Elverum, Norway (605 ng m$^{-3}$), during the winter of 2002, in a suburban atmosphere, and the 713.0 ng m$^{-3}$ recorded at Tengchon, China, during the spring of 2004, in a rural site, suggesting that the main sources of levoglucosan in such places can be attributed to the combustion of firewood and agricultural and garden-waste burning [34,35]. However, the concentrations of levoglucosan found in the present study were significantly higher than those observed in the rural atmosphere in K-puszta, Hungary (12.3 ng m$^{-3}$) during the summer of 2003 (which was characterized by intense solar radiation) [36]; in an urban zone of Copenhagen, Denmark, by Oliveira et al. (2007) (40 ng m$^{-3}$) during the winter season [37]; and in Barcelona, Spain, during the Winter season, in an urban atmosphere, by Reche et al. (2012) (60 ng m$^{-3}$) [38] (Table 6). Regarding the observed differences in levoglucosan concentration, Liu et al. (2005) mentioned that it is also important to consider different emission fluxes for different biomass combustion types, such as fuel types, oven types, agricultural fires and forest fires, among others [39].

Likewise, comparisons of dicarboxylic acid concentrations observed in this study with other studies conducted in other urban areas showed that the average concentration of dicarboxylic acids (70.3 ng m$^{-3}$) was higher than that reported by Balla et al. (2018) (21.0 ng m$^{-3}$) in a suburban area of the city of Thessaloniki, Greece [40], Pietrogrande and Bacco (2011) (12.6 ng m$^{-3}$) in an urban area of the city of Ferrara, Italy [41], and Ho et al. (2006) (60.3 ng m$^{-3}$) in an urban zone of Hong Kong, China [42]. Conversely, it is lower than the reported results by Wang et al. (2002) in urban atmosphere from Nanging, China (128.2 ng m$^{-3}$) [43], and Choi et al. (2016) in an urban zone of the city of Seoul, S. Korea (99.2 ng m$^{-3}$) [44]. Such differences can be attributed to an increase in burning for residential heating in cold periods [19]. However, other studies reported that some of the DCAs tend to be higher during the warm season in urban areas, mainly due to photochemical activity [45]. In this sense, it is
important to highlight that the period in which the present study was carried out was a warm season with the presence of many forest fire events (Table 6).

3.2.4. Water-Soluble Potassium (K⁺)

To evaluate the degree of association between water-soluble potassium and levoglucosan, both considered as indicators of biomass burning, a time-series analysis was performed with the observed concentrations during the study period. Figure 5 reveals two peaks on the days when the highest number of forest fires occurred in the state of Morelos (April–May 2016), confirming the hypothesis that both are indicators of biomass burning. This behavior is consistent with that observed by Zhang et al. (2010) in a study conducted in the urban areas of some cities in the Southwestern United States during winter, when there was an increase in biomass burning [46]. Likewise, Reche et al. (2012) observed similar behavior in the urban area of Barcelona, in biomass burning scenarios [38]. Locker (1988) established the K⁺/levoglucosan relationship to determine if the combustion processes correspond to ovens or fireplaces that use wood, or open fires. If the K⁺/levoglucosan ratio is <0.2, it may indicate the prevalence of domestic heating with wood, while a K⁺/levoglucosan ratio around 0.5 may indicate open fires or combustion of fuels such as slash, or straw [47]. In the present study, the value was 0.44, probably indicating that open fires are the main source of these tracers in the study region.

![Figure 5. Association between water-soluble potassium and levoglucosan.](image)

3.3. Sources of Molecular Markers

In order to investigate possible correlations between the studied compounds, meteorological data and criteria pollutants, the Spearman correlation coefficients were calculated (Table 7).
Table 6. Comparison with other studies carried out in other cities of the world, average concentration (ng m\(^{-3}\)).

| Reference                        | Site                  | Background | Date                  | Size Particle | Levoglucosan | Glutaric | Malonic | Succinic |
|----------------------------------|-----------------------|------------|-----------------------|----------------|--------------|----------|---------|----------|
| Yttri et al., 2007 [34]          | Elverum, Norway       | Suburban   | September–October 2002| PM\(_{10}\)     | 605          | nr       | nr      | nr       |
| Engling et al., 2011 [35]        | Tengchon, China       | Rural      | April–May 2004        | PM\(_{2.5}\)    | 713          | nr       | nr      | nr       |
| Stone et al., 2008 [23]          | México City, México   | Urban      | 16–30 March 2006      | PM\(_{2.5}\)    | 151.3        | nr       | nr      | nr       |
| Ion et al., 2005 [36]            | K-puszta, Hungary     | Rural      | June–July 2003        | PM\(_{2.5}\)    | 12.3         | nr       | nr      | nr       |
| Oliveira et al., 2007 [37]       | Tengchon, China       | Rural      | April–May 2004        | PM\(_{2.5}\)    | 40           | nr       | nr      | nr       |
| Mancilla et al., 2016 [24]       | Monterrey, México     | Urban      | May–June 2011         | PM\(_{2.5}\)    | 54.3         | nr       | nr      | nr       |
| Reche et al., 2012 [38]          | Barcelona, Spain      | Urban      | February–March (2009) | PM\(_{2.5}\)    | 60           | nr       | nr      | nr       |
| Balla et al., 2018 [40]          | Thessaloniki, Greek   | Suburban   | November–December 2014| PM\(_{2.5}\)    | nr           | 26       | nr      | 16       |
| Pietrogrande and Bacco, 2011 [41]| Ferrara, Italy        | Urban      | 2011–2014             | PM\(_{2.5}\)    | 254          | 14.7     | 4.3     | 18.9     |
| Wang et al., 2002 [43]           | Nanjing, China        | Urban      | February–March 2001   | PM\(_{2.5}\)    | nr           | 64.1     | 125.5   | 195      |
| Choi et al., 2016 [44]           | Seoul, South Korea    | Urban      | April 2010–April 2011 | PM\(_{10}\)     | nr           | 10.6     | 191.8   | 95.3     |
| Ho et al., 2006 [42]             | Hong Kong, China      | Urban      | December 2003–February | PM\(_{2.5}\)    | nr           | 20       | 89.1    | 71.9     |
| This study                       | Cuernavaca, México    | Urban      | February–August 2016  | PM\(_{2.5}\)    | 367.6        | 63.2     | 46.9    | 101.7    |

nr: not reported.
Table 7. Correlations between meteorological parameters, criteria air pollutants and organic pollutants evaluated in Cuernavaca (Site 1) in 2016.

|                | SO_2 (ppm) | NOx (ppm) | O_3 (ppm) | PM_2.5 (µg m^−2) | Levoglucosan (ng m^−3) | Glutaric (ng m^−3) | Malonic (ng m^−3) | Succinic (ng m^−3) | T (°C) | RH (%) |
|----------------|------------|-----------|-----------|------------------|-------------------|-------------------|------------------|------------------|-------|-------|
| NOx            | 0.8368     |           |          |                  |                   |                   |                   |                   |       |       |
| CO             | 0.5641     | 0.4881    |          |                  |                   |                   |                   |                   |       |       |
| O_3            | −0.4561    | −0.4172   |          |                  |                   |                   |                   |                   |       |       |
| PM_2.5         |            |           |          | 0.6727           |                   |                   |                   |                   |       |       |
| Levoglucosan   | 0.4900     | 0.7076    |          |                  |                   |                   |                   |                   |       |       |
| Glutaric       | 0.6365     | 0.7179    |          | 0.5764           |                   |                   |                   |                   |       |       |
| Malonic        | 0.4840     | 0.6918    |          | 0.6459           | 0.7165            |                   |                   |                   |       |       |
| Succinic       |            |           |          | 0.4598           | 0.5766            |                   |                   |                   |       |       |
| K^+            |            |           |          |                  |                   |                   |                   |                   |       |       |
| T              | 0.7148     | 0.5912    |          | −0.4566          | −0.5649           | −0.5043           | −0.5196          | −0.3973          | −0.4410 | −0.4276 |
| SR             | −0.3995    |          |          |                  |                   |                   |                   |                   |       | −0.5093 |

Italic values (p < 0.05); ppm (parts per million), SR (Solar radiation), RH (Relative humidity).

Levoglucosan positively correlated with glutaric and malonic acids and K^+, probably indicating common sources, i.e., from biomass burning and mainly cellulose pyrolysis [48,49]. The positive correlation observed between temperature and O_3 with glutaric and malonic acids and levoglucosan suggests the incidence of photochemical activity. Specifically, for the observed correlation between temperature and malonic and glutaric acids, Ho et al. (2006) indicates that this behavior is associated with secondary photochemical processes in the atmosphere rather than primary emissions from vehicular exhaust [19]. Other studies suggest that glutaric acid has a mechanism of formation through secondary photochemical reactions in the atmosphere, from vehicle emissions [33,50]. The positive correlation observed between temperature and levoglucosan can be attributed to the large number of forest fires that occurred in the study season in the state of Morelos. The positive correlation between PM_2.5 and glutaric and malonic acids and levoglucosan suggests that such compounds are contributing to secondary organic aerosol particles’ formation. Gaseous pollutants (NO_x, CO and SO_2) did not show a correlation with levoglucosan, as these compounds are mainly generated by exhaust emissions from local sources.

Finally taking into account the recommendations established in the European guide for estimating sources of air pollution, a Factor Analysis with Varimax rotation was performed, only to determine a preliminary overview of the possible sources of the compounds studied for the Centro site [51].

Three factors were extracted that explained 84.7% of the total variance (Table 8). The first factor, accounting for 30.7% of the variance, was mainly constituted by glutaric, malonic, and succinic acids and temperature, suggesting photochemical formation, possibly by precursors from vehicle exhausts. The second component explained 25.45% of the variance, clearly indicating local vehicle emissions. The third factor explained 28.55%, conformed mainly by K^+ and levoglucosan, indicating the incidence of common sources, i.e., the burning of biomass (Table 8).

Table 8. Factor analysis with Varimax rotation realized for the Centro site.

|                | Factor 1 | Factor 2 | Factor 3 |
|----------------|----------|----------|----------|
| CO             | 0.3704   | 0.7444   | 0.0325   |
| NOx            | −0.1272  | 0.8749   | −0.0623  |
| O_3            | 0.4558   | −0.3500  | 0.5196   |
| SO_2           | −0.2076  | 0.8954   | −0.0730  |
| K^+            | 0.0884   | 0.0256   | 0.8402   |
| Glutaric       | 0.8100   | −0.1573  | 0.2544   |
| Malonic        | 0.8559   | 0.1196   | 0.2835   |
| Succinic       | 0.7106   | −0.1516  | −0.2320  |
| Levoglucosan   | 0.5699   | −0.0948  | 0.6763   |
| % RH           | −0.5174  | 0.7036   | −0.1483  |
| SR             | 0.3218   | −0.5205  | −0.4089  |
| T              | 0.6711   | −0.1668  | 0.2128   |
4. Conclusions

This is the first study carried out in Cuernavaca in which the concentration of molecular markers associated with the burning of biomass was determined. It is clearly observed how, in the fire season, the concentration of such compounds is significantly increased, which contributes significantly to the deterioration of air quality in this zone and has possible implications for climate change.

The impact of biomass burning was observed by means of tracers such as levoglucosan and K\(^+\). The results showed that the high PM\(_{2.5}\) concentrations and molecular tracers coincided with the fire season. The C\(_3\)/C\(_4\) ratio observed in this study suggested that, in the urban area of Cuernavaca, photochemical processes regulate, to a large extent, the presence of the dicarboxylic acids studied. Likewise, the K\(^+\)/levoglucosan ratio reveals the relevance of open fires in the region’s air quality.

The Factor Analysis gave us an overview of the possible contribution of sources of the compounds studied in the region, however, to make a more precise estimate of the possible sources, it is required to apply more advanced models, such as PMF and CMB. These software programs will be applied in the next stage of the project, in which more sampling sites and more samples will be considered.

Finally, these results constitute a call to the environmental authorities for attention to the implementation of environmental education campaigns, as well as for the generation of strategies that allow for prevention, to a large extent, of the indiscriminate burning of plant material.

Author Contributions: Conceptualization, H.S.-N. and M.I.A.-M.; methodology, J.A.G.-A., P.G.R. and S.M.-P.; investigation, J.V.-S., F.R.-Q. and M.A.M.-T.; writing—original draft preparation, H.S.-N. and R.L.-M. All authors have read and agreed to the published version of the manuscript.

Funding: Authors would like to thank Consejo Nacional de Ciencia y Tecnología (CONACYT) for the studentship and Laboratorio Nacional de Estructura de Macromoléculas (LANEM CONACyT/251613).

Acknowledgments: The authors wish to thank the Program for the Development of Teachers (PRODEP, by its acronym in Spanish) for its support in the financing of this publication and the National Laboratory of Macromolecule Structure (LANEM, by its acronym in Spanish) for allowing us to use its laboratories and infrastructure.

Conflicts of Interest: The authors declare no conflict of interest.

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