



Review

Saccharides as Particulate Matter Tracers of Biomass Burning: A Review

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Abstract: The adverse effects of atmospheric particulate matter (PM) on health and ecosystems, as well as on meteorology and climate change, are well known to the scientific community. It is therefore undeniable that a good understanding of the sources of PM is crucial for effective control of emissions and to protect public health. One of the major contributions to atmospheric PM is biomass burning, a practice used both in agriculture and home heating, which can be traced and identified by analyzing sugars emitted from the combustion of cellulose and hemicellulose that make up biomass. In this review comparing almost 200 selected articles, we highlight the most recent studies that broaden such category of tracers, covering research publications on residential wood combustions, open-fire or combustion chamber burnings and ambient PM in different regions of Asia, America and Europe. The purpose of the present work is to collect data in the literature that indicate a direct correspondence between biomass burning and saccharides emitted into the atmosphere with regard to distinguishing common sugars attributed to biomass burning from those that have co-causes of issue. In this paper, we provide a list of 24 compounds, including those most commonly recognized as biomass burning tracers (i.e., levoglucosan, mannosan and galactosan), from which it emerges that monosaccharide anhydrides, sugar alcohols and primary sugars have been widely reported as organic tracers for biomass combustion, although it has also been shown that emissions of these compounds depend not only on combustion characteristics and equipment but also on fuel type, combustion quality and weather conditions. Although it appears that it is currently not possible to define a single compound as a universal indicator of biomass combustion, this review provides a valuable tool for the collection of information in the literature and identifies analytes that can lead to the determination of patterns for the distribution between PM generated by biomass combustion.

Keywords: biomass burning; saccharides; anhydrosugars; sugar alcohols; tracers; PM



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1. Introduction

Any solid or liquid fuel combustion event generates airborne material that negatively affects air quality and health. This is due to the fact that volatile and unburnt products are inevitably generated by combustion processes that cannot in any way be ideal [1,2]. Such combustion events are the major sources of aerosols and exert significance influence on human health, air quality and global climate [3,4].

The term “aerosol” designates the complex of solid and liquid particles suspended in the atmosphere that may vary in size from a few nanometers to tens of microns [5]. Depending on their origin, aerosols may be natural or anthropogenic and may consist of mixtures of organic and inorganic compounds, primarily emitted or formed in the

atmosphere from precursor gases (secondary aerosols), exhibiting a broad and complex spectrum of physical and chemical properties, which actively contribute to their climate and health-related effects [4,6]. Organic aerosols are the essential components of airborne particulate matter (PM), globally recognized as one of the main environmental and health risk factors contributing to the development or exacerbation of many diseases [7].

Epidemiological studies have found strong relationships between cardiovascular outcomes, respiratory illnesses and asthma and the high level of organic aerosols in the atmosphere [8]. Studies on pollution levels provided evidence concerning premature mortality in Europe, which totals at least 40,000 premature deaths per year [9]. Several experimental studies attribute the onset of adverse health effects, such as eye and throat irritation, to wood smoke, and inhalation studies have demonstrated that wood smoke exposure may induce systemic effects, providing a possible link to cardiovascular effects [9,10].

Evidence from a large number of studies shows that organic aerosols affect not only human health but also influence climate. They have become a topic of great interest because of their influence on radiative forcing, biogeochemical cycles and atmospheric chemistry [11–13].

Jimenez et al., 2009 [14] stated that organic aerosol (OA) can modify the earth's climate through scattering and absorption of solar radiation, altering cloud properties and lifetime, whereas Cao et al., 2012 [15] considered the ability of particles to reduce visibility by causing uptake of water into the aerosol.

Accounting for 18–38% of the fine OA [16], biomass burning significantly contributes to the emission of gases and toxic compounds in the atmosphere [17,18], and it has been identified as a biofuel that may contribute to the worsening of both outdoor and indoor air quality [19]. In central and northern Europe, biomass burning emissions have been recognized as one of the major sources of organic aerosols during wintertime, contributing, as domestic heating, to air quality degradation in many Mediterranean urban areas [20–22]. In addition to biomass burning for residential heating, burning of agricultural waste is a common practice that emits relevant amounts of gaseous and particulate pollutants into the atmosphere [23,24]. In developing countries, although environmentally unacceptable, *open burning* is a widespread practice used as a rapid, cheap and easy method for disposing of crop residues, releasing nutrients for the next growing cycle and clearing lands [25].

Nowadays, renewable energy sources in the form of solid biomass are becoming increasingly important in order to replace fossil fuels and reduce greenhouse gas emissions [26,27]. Solid waste biomass may be an alternative to conventional energy sources, mostly in the form of compressed biofuels; briquettes or pellets have the advantages of high density, lower moisture and better physical homogenization. There are many specific papers focused on the characterization, production and energy evaluation of such biomass materials as fuels [28,29], which represent an important opportunity in the renewable energy field.

This study seeks to collect and define the information available in the literature on the set of biomarkers that contribute to the PM produced both by natural phenomena and by conversion processes of energy from biomass in order to be able to differentiate the PM emitted by natural or anthropogenic activities (such as the use of fossil fuels).

In this review, biomass burning is observed in the form of open burning of agricultural residues, grassland and forest fires, and residential combustion of biomass for cooking and heating purposes. In this context, the most widespread biofuels include both crop waste, such as rice straw, maize residue, wheat residues and bean straw [30]; and woody fuels, such as branches and wood [31].

Although in the literature, there are several studies aimed at determining sugar compounds present in PM emitted from anthropogenic or natural sources [32–36] and there are also numerous studies based on the source apportionment of such aerosols [37–42], to the best of our knowledge, there is a lack of studies related to determination and quantification of such compounds as possible tracers useful for the discrimination of PM emitted by

biomass combustion. The purpose of this review differs from that of the aforementioned papers, bringing together multiple results concerning biomass-derived saccharides.

2. Methodology

A collection of data in the global scientific literature was conducted to determine which saccharide compounds have been observed and quantified during atmospheric monitoring in relation to biomass combustion phenomena and those attributed to natural causes. This was achieved through an extensive literature research (Figure 1) performed of the SCOPUS and the Google Scholar databases, using the keywords: biomass burning, tracers, saccharides, anhydrosugars, sugar alcohols and PM. A total of 198 scientific papers published during the period of 1988–2022 were considered, and it was possible to organize the review work into several sections. Section 3 deals with the characterization of saccharides identified as tracers during environmental monitoring campaigns and summarizes the major source apportionment studies aimed at the identification of such marker compounds; Section 4 presents the results of such identification, and Section 5 provides a summary and concluding remarks for future research directions. Reviewing the extensive literature on aerosol emissions from biomass combustion, in this paper, we aim to provide an overview of the contributions of sugar compounds to PM, synthesizing results from published literature and summarizing the factors governing such emissions.

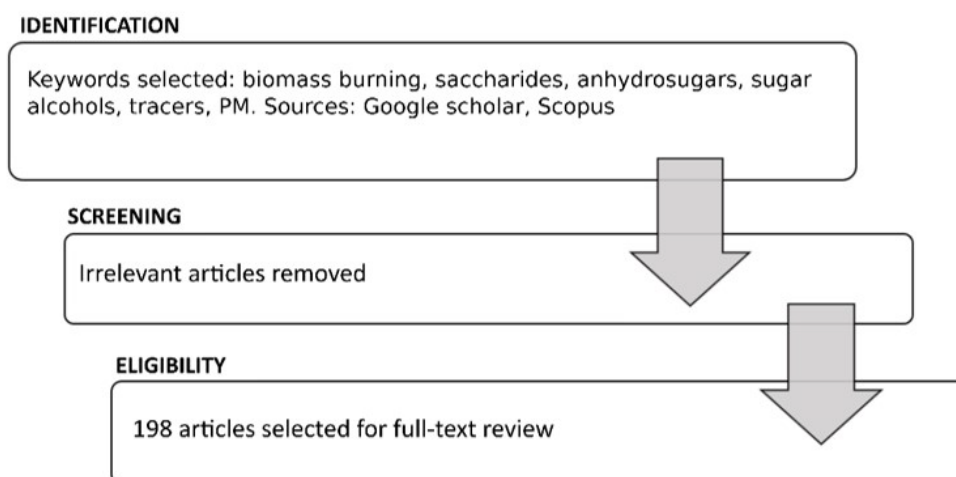


Figure 1. Flowchart describing the literature research and article selection.

3. Biomass Burning

Biomass is rich in saccharides in the form of oligosaccharides and polysaccharides, such as cellulose, lignin and starch, which, upon combustion, produce significant amounts of monosaccharides, disaccharides, sugar alcohols and anhydrosugars, in addition to other simple molecules [43]. Such saccharide compounds are one of the major classes often utilized as biological markers for atmospheric aerosols [44–46], and by virtue of their ubiquity and size-resolved chemical composition, they have offered the opportunity to estimate the atmospheric trajectory and sources of aerosol particles [47–49]. The anhydro saccharides levoglucosan (L), mannosan (M) and galactosan (G) originate from the combustion of cellulose and hemicellulose and are accordingly recognized as biomass-burning markers [50–52]. Primary saccharides such as glucose, sucrose and fructose are characteristic of material such as pollen, fruit, and plant fragments [53], whereas sugar alcohols, such as mannitol and arabitol are characteristic of fungal spores [54]. However, several studies have attributed biomass burning as the source of these last two categories of saccharides, finding possible causes of increased concentrations of such saccharide compounds in the atmosphere in the volatilization from breakdown of polysaccharides and in hydrolysis in conditions of atmospheric acidity during burning [55–58].

Table S1 shows a list of such saccharide compounds monitored and emitted from natural or anthropogenic sources, with their respective concentrations, locations, PM fractions, technique, background and period of monitoring. Not all studies have as their main objective the quantification of the identified compounds, so some studies, such as [59] and [60], do not present the concentrations of the identified saccharides.

Characterizing compounds at a particle scale can thus improve our knowledge of the composition of aerosols from combustion-related emission [36]. Studies have focused on the seasonal and temporal variations of atmospheric sugars in several areas throughout the world [61–64]. Research in this field is crucial because it provides useful data regarding the sources and processing of aerosols released into the atmosphere from biomass burning, soil dust and primary biological aerosols, such as fungal spores and pollen, all of which have a considerable impact on the environment.

3.1. Tracers

As mentioned above, biomass burning is an important primary emitter of several trace organic compounds that are reactive in the atmosphere, as well as of soot particles, which decrease visibility and absorb incident radiation [65,66]. For this reason, the composition of atmospheric aerosols has received increasing attention, aimed at determining the contributions of the various emission sources to environmental PM. Khalil and Rasmussen, 2003 [67] argued that a tracer may be considered ideal when certain peculiar characteristics are met: it has to be resistant to degradation, source specific and constant and allow for high-precision measurement. However, some factors, such as the complex chemical combustion conditions, the high inhomogeneity of the particles, the different types of biofuel used, the operating conditions or the formation of ash, can make it difficult to find a tracer that meets all of these characteristics at once [68–74]. Water-soluble potassium (K^+) has been proposed as a tracer for biomass burning in receptor models due to its ubiquity in the cytoplasm of plants [75], and a strong positive correlation was observed among K^+ , organic carbon (OC), elemental carbon (EC) and WSOCs (water-soluble organic compounds) that indicated crop residues burning to carbonaceous aerosols [76]. Several studies in the literature have also proposed the use of the levoglucosan to K^+ ratio to distinguish the particular plant species of BB activities in atmospheric aerosols [77]. However, fertilizers and soil dust resuspension in rural areas [18,78,79], as well as meat cooking and refuse incineration in urban areas [80–82], produce and release K^+ in the atmosphere, leading to many limitations in the use of this marker.

Factors such as varying temperature conditions, aeration, heating temperature, and smoldering and flaming conditions contribute to determining the nature and amounts of the combustion products [83]. Due to their source-specific origins, some thermally altered molecules can therefore be used as chemical fingerprints and be useful in determining the contributions of the burning of different biomasses to atmospheric particulate matter.

Research conducted in recent years indicates that anhydrosugars can be produced and emitted into the atmosphere by the burning of coals, especially lignites [84,85]. This is noteworthy, considering that in some countries, such as Poland and China, emissions of carbonaceous PM are highly connected with coal burning [86–88], and this inevitably associates the emission of a portion of detected anhydrosugars with such coal fuels. Admittedly, this is not the issue that this work is concerned with, and deeper insights are provided in the literature [51,89,90].

3.2. Source Apportionment Studies

Air quality is strongly affected by PM emissions generated by multiple sources, such as industrial processes, vehicular traffic, power plants, combustion of agricultural and food residues, and uncontrolled forest fires [91,92]. Accurate analysis of pollutant sources and their components is a crucial step toward developing efficient control strategies and reducing the harmful effects of particulate matter [93–95]. Among the developed methods, the receptor model is a widely used tool for PM source apportionment (SA) studies. Such

methods can be categorized into univariate models, e.g., chemical mass balance (CMB), and multivariate models, such as positive matrix factorization (PMF), principal component analysis (PCA) and the EPA's Unmix model [96,97]. However, the CMB model has limited application because it requires prior knowledge about source profiles and, in order to achieve quantitative SA, needs to be associated to other methods. On the other hand, the Unmix model does permit quantification of the source contribution, although it cannot separate sources that have similar contributions to particle mass [98]. In contrast, PMF is a multivariate chemical receptor model based on factor analysis developed by Paatero at the University of Helsinki, Finland [99,100]. Briefly, this receptor model can estimate the factor profiles and corresponding relative contributions during the sampling period based on a large amounts of observation data, overcoming the aforementioned problems using a least-square method to assess the source profiles and their contributions to particle mass [101,102].

Further explanation of receptor models, their assumptions and applications can be found in [103–106].

In the context of the literature studies we reviewed, many have used these SA methods to identify and quantify the contribution of biomass burning to total atmospheric PM, allowing for attribution of the presence of saccharides in the air to both biogenic and anthropogenic factors, such as biomass burning. Table 1 shows the main source apportionment studies that have attributed sugars to biomass burning and natural sources. As can be seen, the most commonly used SA technique is PMF, followed by PCA.

Thus, levoglucosan and its isomers are used as specific chemical markers to identify biomass-burning-derived emissions and help in source apportionment approaches. Such compounds have been used in studies around the world: in Europe [84,107–110], North and South America [111–113], as well as Asia [114–119].

Additionally, sugar alcohols such as inositol and arabitol have been proposed as biomass-burning-derived tracers. Originated from the metabolism of fungi and found on leaves of trees, such carbohydrates are also emitted from open-air combustion [120], stoves [121] and combustion chambers [122]. Thus, concentrations of sugar alcohols, in combination with high levels of levoglucosan, indicate that biomass combustion contributes to the aerosol content, resulting in their classification as biomass burning markers.

Table 1. Source apportionment studies most used in the evaluation of saccharide compounds present in airborne particulate matter.

Compound	Source	SA Study	Reference
<i>Anhydrosugars</i>			
<i>Levoglucosan</i>	biomass burning	PMF	[43,123–125]
	biomass burning	PCA	[60,126–128]
<i>Mannosan</i>	biomass burning	PMF	[43]
	biomass burning	PCA	[60,126–128]
<i>Galactosan</i>	biomass burning	PMF	[43]
	biomass burning	PCA	[60,126–128]
<i>Sugar alcohols</i>			
<i>Inositol</i>	biomass burning	PCA	[58]
	fungal spores	PMF	[129]
	plants	PMF	
<i>Arabitol</i>	soil dust		[130]
	pollen	PMF	[131]
	yeasts, fungal spores	PMF	[43,132]
	fungal spores	PCA	[126]
	biomass burning	PCA	[58,133]
<i>Mannitol</i>	yeasts, fungal spores	PMF	[43,131,132]

Table 1. *Cont.*

Compound	Source	SA Study	Reference
<i>Erythritol</i>	fungus spores	PCA	[126,134]
	biomass burning	PCA	[58,133]
	plants, soil	PCA	[128]
	biomass burning	PMF	[43]
	biomass burning	PCA	[58,134]
	fungus spores	PCA	[134]
<i>Glycerol</i>	plants, biota	PCA	[129,133]
	biomass burning	PMF	[43,124]
	soil	PCA	[60]
<i>Xylitol</i>	biomass burning	PCA	[58]
	biomass burning	PCA	[58]
	plants, biota	PCA	[133]
<i>Ribitol</i>	biomass burning	PMF	[125]
	plants, biota	PCA	[128]
<i>Threitol</i>	biomass burning	PMF	[132]
	plants	PMF	[132]
<i>Methyltreitol</i>	plants	PMF	[132]
Monosaccharides			
<i>Glucose</i>	pollen, pollen, fruits,	PMF	[131]
	fungus spores	PCA	[134]
	biomass burning	PCA	[58,60,128,133]
	soil, biota	PMF	[43,58]
<i>Fructose</i>	pollen fruits, plants	PMF	[131]
	fungus spores	PCA	[127,134]
	soil	PMF	[43]
<i>Galactose</i>	plants	PCA	[127]
	biomass burning	PMF	[43]
	biomass burning	PCA	[128]
<i>Arabinose</i>	biomass burning	PCA	[128]
<i>Mannopyranose</i>	soil, biota	PCA	[133]
<i>Xylose</i>	biomass burning	PCA	[60]
	plants	PCA	[129]
Disaccharides			
<i>Maltose</i>	biomass burning	PCA	[127]
	plants	PCA	[127]
<i>Sucrose</i>	plants, pollen, fruits	PMF	[131]
	plants	PCA	[127]
	pollen	PCA	[60,134]
	fungus spores	PCA	[129]
<i>Trehalose</i>	soil, biota	PMF	[43]
	yeasts, fungus spores	PCA	[127]
	soil biota	PCA	[58,133]
	biomass burning	PCA	[133]
	plants	PMF	[129]
	soil dust	PMF	[129,131]
	soil dust	PCA	[60]

4. Saccharides

Sugar compounds have been proposed both as tracers for determining the sources, processes and paths of aerosols emitted by biomass burning and for elucidating the atmospheric level of naturally emitted aerosols [131,135,136].

The organic matter in biomass is constituted of a large amount of biopolymers, such as cellulose, hemicellulose and lignin. Cellulose, providing a supporting fibrous mesh reinforced by lignin, is a long-chain linear polymer made up of 7000–12,000 D-glucose monomers able to organize to form parallel fiber structures [137], whereas hemicellulose

consists of only about 100–200 sugar monomers, such as glucose, mannose, galactose and xylose, and a less intricate structure. Lignin is a coniferyl- and sinapyl-derived *p*-coumaryl and contains tannins and terpenes, which makes it a complex substance [19,138]. The biomass combustion process, which involves hydrolization, oxidation, dehydration and pyrolyzation phases, leads to the formation and emission of important classes of sugars, which are therefore source-specific [139,140] because, although they are also emitted from other sources (e.g., lignite or low-grade coal), the contribution of such sources can be considered negligible due to their extremely low emission rates [83,141] (Figure 2).

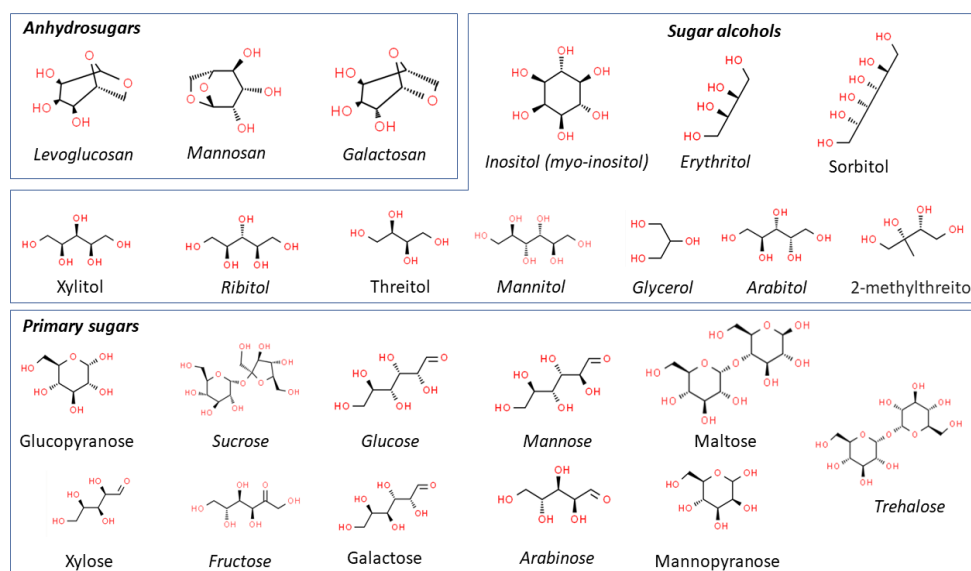


Figure 2. Chemical structures of saccharide compounds detected in atmospheric monitoring studies.

The main class of sugar compounds emitted by biomass combustion is anhydrosugars; in particular, levoglucosan, together with its mannosan and galactosan monomers, is the most commonly used tracer for the assessment of PM from biomass burning. Moreover, the ratio between levoglucosan and mannosan has been used to distinguish the contributions of hard and softwood to wood-combustion-related PM [142].

Sugar alcohols, such as arabitol, mannitol and inositol, are another class of sugars present in the atmosphere but emitted by biogenic sources, such as metabolism of fungi [143,144]. Many studies have focused on the existing correlation of these compounds with the anhydrosugars emitted by burning, showing that the presence of sugar alcohols, in combination with high-levels of levoglucosan and its isomer, specifically indicates that biomass burning has contributed to the aerosol content [61,145].

Mono- and disaccharides from soils and associated biota can be emitted in the atmosphere through resuspension, erosion and agricultural activities [35,146,147]. Glucose, fructose and sucrose may derive from plant pollen and developing leaves [63,131]. In light of the relevant presence of such compounds in airborne particulate matter, a comprehensive field study on the molecular and seasonal variation of atmospheric saccharides may improve our understanding of the biogenic origins of aerosol particles besides the anthropogenic sources [148].

With regard to the detection of saccharides in the monitoring campaigns that make up this review paper, the particulate fraction most investigated and in which all the categories of sugars are placed to a greater extent is PM_{2.5}, followed by PM₁₀ fraction and, finally, the fraction that includes particles with an aerodynamic diameter lower than 1 µm (PM₁) [58,149].

As far as the improvement of our knowledge is concerned, increasing scientific efforts have been demonstrated in the quantification of sugars. The most widespread analytical method for analysis of such compounds in atmospheric samples is the gas chromatographic technique coupled with mass spectrometry (GC-MS) [52,144,150,151], which guarantees

high selectivity and specificity offered by the capillary columns and the m/z values in the mass spectra, respectively [152]. Limitations to such a chromatographic approach include the need for large sample mass and sample workup (e.g., solvent extraction, extract concentration and derivatization). As an alternative, liquid chromatography techniques, in the form of HPAEC-PAD (high-performance anion-exchange chromatography coupled with pulsed amperometric detection), HPAEC-MS (high-performance anion-exchange chromatography coupled with mass spectrometry), IC-PAD (ion chromatography with pulsed amperometric detection) and IC-MS (ion chromatography coupled with mass spectrometry) have been widely used to directly analyze organic compounds in aqueous filter extracts, allowing for simultaneous analysis of different sugar compounds [153,154]. An overview of the most widely used techniques revealed in this work is shown in Figure 3.

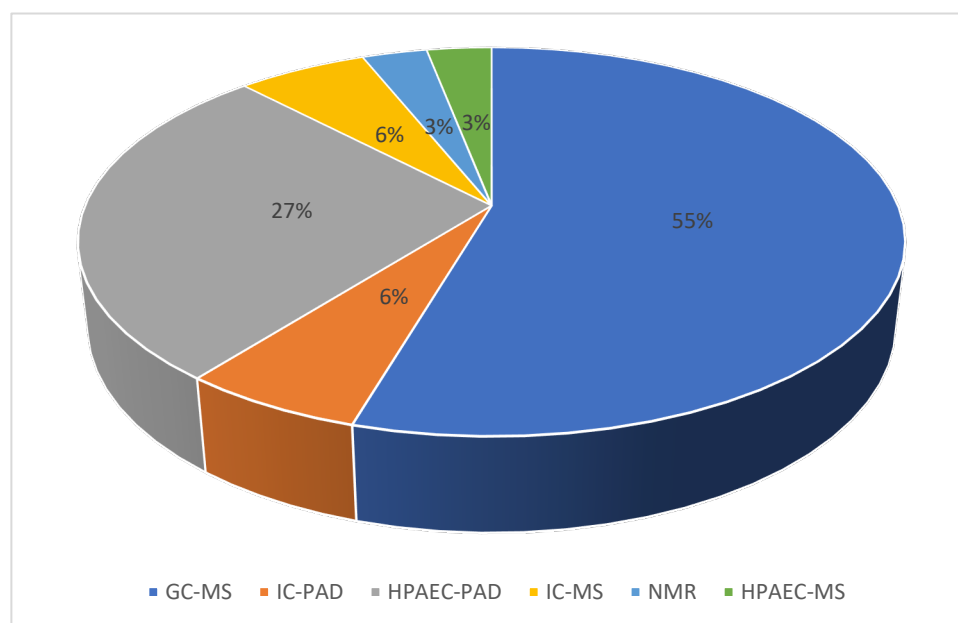


Figure 3. Most utilized techniques found in the literature for sugar compound determination in PM aerosol analysis (based on data from Supplementary Materials Table S1).

4.1. Anhydrosugars

Among the several categories of chemical compounds emitted by the combustion of biomass, anhydrosugars are the most frequently identified.

Levoglucosan (*1,6-anhydro- β -D-glucopyranose*) and its isomers, mannosan (*1,6-anhydro- β -D-mannopyranose*) and galactosan (*1,6-anhydro- β -D-galactopyranose*), are the most used organic tracers to assess the contribution of biomass burning to atmospheric particulate matter because, due to their low vapor pressure, they are easily found in the atmosphere as a consequence of the pyrolysis and the thermal breakdown of cellulose [10,155–158]. The presence of anhydrosugars in the ambient air has been demonstrated in emissions from prescribed and agricultural fires [44,159,160], as well as from residential wood combustion and wildfires [121,161,162].

The atmospheric concentrations of levoglucosan have shown a high variability depending not only on the type of fuel and appliance utilized but also on meteorological parameters. In a one-year PM monitoring study, Oduber et al., 2021 [161] stated that lower autumn temperatures favored an increase in the concentrations of anhydrosugars due to the increasing use of domestic heating devices. Moreover, mannosan was correlated not only with OC, EC, Pb and other heavy metals, which are fossil fuel and traffic combustion markers, but it was also correlated with As, a coal combustion marker. This result led the authors to conclude that the selection of such anhydrosugars as biomass burning tracers during the cold season may overestimate the contribution of that source because of other anthropogenic emission factors. Thus, among the numerous studies present in

the literature, some cast doubt on the possibility of using anhydrosugars, particularly levoglucosan, as biomass burning tracers. Following controlled combustion experiments, some authors [163,164] came to the conclusion that the levoglucosan fraction relative to particle mass may be highly dependent on combustion parameters and that a variable that strongly influences the yield of levoglucosan is the presence of inorganic ions in the biomass [165,166], as the amount of mineral matter reduces the temperature of cellulose pyrolysis [167]. Hence, qualitative and quantitative estimates of biomass burning emissions to atmospheric PM using only levoglucosan as a marker may be unfounded.

As previously mentioned, galactosan and mannosan also contribute to biomass burning emissions, and their concentrations are strongly dependent on the biomass burned (e.g., hardwood or softwood). Based on the results available in the literature, in Table 2, the main sugars detected in different matrices burned by means of different appliances are reported.

In light of this, the simultaneous quantification of anhydrosugars is desirable in order to assess the contribution from distinct biomass burning emissions. Hence, the relative proportions of levoglucosan to mannosan (L/M) have been used for source reconstruction of combustion-derived byproducts in atmospheric aerosols. Differences in the L/M ratio in smoke from softwood and hardwood grass combustion further support discrimination between inputs from these combustion sources to the atmosphere [50]. Relatively high L/M ratios in the range of 25 to 50 can be produced by herbaceous tissues [168]. Schmidl et al. 2011 [168] investigated two automatically and two manually fired appliances, as well as eight biofuels. Detectable amounts of anhydrosugars are only emitted in the start-up phase of automatically fired systems. L/M ratios of around 14–17 for hardwoods and of 2.5–3.5 for softwood combustion using manually fired appliances were found, whereas during combustion in a biomass boiler, the authors reported L/M ratios of 2.3–2.9 for wood pellets, 1.7 for wood chips made of softwood and higher values for miscanthus and triticale pellets, which behave similarly to hardwoods. Alves et al., 2017 [169] reported that anhydrosugars represented 2.3–3.5 and 0.73–1.7 wt.% of the OC mass in emissions from the combustion of pellets and agrofuels, respectively, in a pellet stove. The authors came to the conclusion that the anhydrosugar mass fractions were 30 to 70 times lower than the amount reported for manually fired systems.

As noted by numerous studies, the levoglucosan-to-OC ratio has been shown to be highly variable in biomass burning emissions. Fine et al., 2001 [170] carried out tests to determine the chemical composition of fine PM emissions from the fireplace combustion of six species of wood grown in the northeastern United States. The authors found higher levoglucosan concentrations from hardwood than softwood biomass. Levoglucosan yields in the range of 0.109 to 0.168 g g⁻¹ OC and 0.052 to 0.095 g g⁻¹ OC were reported for hardwood and softwood combustion, respectively. On the other hand, softwood combustion usually produced higher mannosan emissions than those of hardwoods. Mannosan emissions ranged between 0.0013 and 0.0047 and between 0.0090 and 0.025 g g⁻¹ OC for hardwood and softwood combustion, respectively. A later study [171–173] reported a levoglucosan-to-OC mass ratio of 0.136 g g⁻¹ for fireplace combustion of four hardwood species grown in the southern US, which is consistent with the previous results. Furthermore, the researchers also proved the importance of combustion conditions to the anhydrosugars yield. After testing the same wood in a fireplace and in a woodstove, the authors reported that in general, the levoglucosan content in emissions from woodstoves were higher than those obtained from fireplaces. In addition to the L/M ratio, the relative proportion of levoglucosan to galactosan has also been used; in order to evaluate whether anhydrosugar ratios can provide information on the type of biofuel Caumo et al., 2016 [145], studied the levoglucosan-to-galactosan ratio (L/G), considering that hemicelluloses from sugarcane residue have a relatively high galactose (monosaccharide precursor of galactosan) content [17]. Comparing the results obtained in Brazil from an urban site with those obtained from a rural site characterized by sugarcane residue burning, it was found that a ratio value lower than 30 may be attributed to sugarcane burning at a regional scale and not to tropical forest fires affecting those areas.

Table 2. Saccharide compounds detected in aerosols emitted from tree and herbaceous biomass by means of different combustion appliances.

Biomass		Saccharides Detected												Units	Appliance	Ref.
Tree Biomass	Anhydrosugars			Sugar Alcohols					Mono- and Disaccharides							
Hardwood	L	M	G	I-ol	A-ol	M-ol	E-ol	S-ol	G-ose	F-ose	M-ose	S-ose				
Blue gum, Australian blackwood	13.4	7.59	5.2	-	-	-	-	-	-	-	-	74.6 (µg/g)	mg/g	Wildfire	[55]	
Blue gum, Australian blackwood	12.8	5.65	2.8	-	-	-	-	-	-	-	-	-	mg/g	Wildfire	[55]	
Acacia pellet	284	24.2	10.4	-	4.27	-	-	-	-	-	-	-	µg/g	Stove	[173]	
Apple tree branch	3.44	0.22	0.18	<LOD	0.18	0.22	-	-	<LOD	-	-	0.08	mg/kg	Stove	[174]	
Wood branch	5.46	0.36	0.29	<LOD	0.29	<LOD	-	-	<LOD	-	-	0.13	mg/kg	Stove	[121]	
Pear and walnut wood and leaves	2.12	0.412	1.45	-	0.138	<0.005	-	0.23	-	<0.01	<0.01	<0.01	% of total mass	Open air combustion	[143]	
Pear and walnut wood and leaves	2.14	0.36	1.93	-	0.14	0.008	-	0.27	-	<0.01	0.017	<0.02	% of total mass	Open air combustion	[143]	
Red maple	213.16	11.06	3.97	-	-	-	-	-	-	-	-	-	mg/g	Stove	[131]	
Sugar maple	210.07	12.88	2.55	-	-	-	-	-	-	-	-	-	mg/g	Stove	[131]	
White oak	125.14	5.51	6.55	-	-	-	-	-	-	-	-	-	mg/g	Stove	[131]	
<i>Softwood</i>																
Douglas fir	408.8	117.65	24.17	-	-	-	-	-	-	-	-	-	mg/g	Stove	[131]	
Pine trees	13.9	8.4	6.21	-	-	-	-	-	-	-	-	-	mg/g	Wildfire	[162]	
Pine trees	9.65	5.65	4.23	-	-	-	-	-	-	-	-	-	mg/g	Wildfire	[162]	
Loblolly pine	253.11	46.33	11.45	-	-	-	-	-	-	-	-	-	mg/g	Stove	[131]	
Herbaceous biomass																
Brooms, brambles	13.9	8.4	6.21	-	-	-	-	-	-	-	-	-	mg/g	wildfire	[162]	
Rice straw	112	3.14	-	2.23	2.79	1.84	0.8	-	2.59	-	5.76	-	mg/kg	combustion chamber	[175]	
Maize residues	33.5	1.27	-	1.7	1.59	1.23	0.59	-	1.14	-	2.22	-	mg/kg	combustion chamber	[175]	
Leaf litter (ddf)	196	11	-	2.65	5.14	1.97	1.41	-	1.72	-	16.4	-	mg/kg	combustion chamber	[175]	
Wheat straw	96.4	2.12	1.97	<LOD	0.21	0.11	-	-	0.56	-	-	<LOD	mg/kg	Stove	[174]	
Wheat straw, corn straw	0.23	0.01	-	-	-	-	-	-	-	-	-	-	µg/m ³	Stove	[77]	
Wheat straw, corn straw	0.59	0.06	-	-	-	-	-	-	-	-	-	-	µg/m ³	Stove	[77]	

Abbreviation used: "L" = levoglucosan; "M" = mannosan; "G" = galactosan; "I-ol" = inositol; "A-ol" = arabitol; "M-ol" = mannitol; "E-ol" = erythritol; "S-ol" = sorbitol; "G-ose" = glucose; "F-ose" = fructose; "M-ose" = mannose; "S-ose" = sucrose; "LOD" = limit of detection; "-" = not detected or not specified.

4.2. Sugar Alcohols

Sugar alcohols, also referred to as *polyalcohols*, *polyols* or *sacharols*, represent another class of carbohydrate derivatives present in the atmospheric aerosol naturally produced by fungi, lichens, soil biota and algae [176]. Several studies have been undertaken to characterize sugar alcohols in different areas worldwide in order to use them as indicators of biogenic aerosol sources [131,177–180].

The reason why these sugars constituents are primary products of combustion is that they are formed either through direct volatilization from vegetation material or as products of the breakdown of polysaccharides. Some of these saccharide derivatives may also be formed by hydrolysis of the analogous anhydrosugars under the acidic atmospheric conditions produced by biomass burning, as suggested by many authors [55–58,161].

Arabitol and mannitol are two typical sugar alcohols widely monitored, as they make an important contribution to the mass of atmospheric aerosol particles derived from microbially degraded material during the leaf senescence period and from fungal spores [1,54,144,181–183]. In an atmospheric monitoring study in China, Kang et al., 2017, [181] found higher levels of mannitol and arabitol in spring likely, due to the blossoming of vegetation, and higher glycerol, arabitol and erythritol levels during winter and autumn, i.e., when vegetation decays and the fungal population increases. On the other hand, higher wintertime concentrations may be attributed to intense open burning of crop residues and indoor biofuel utilization for heating or cooking. Many other studies have suggested combustion sources of these compounds [57,58,133].

Zhang et al., 2013 [182] studied emissions from different types of biomass burning and proposed arabitol and inositol as useful tracers for green foliage combustion due to their higher concentrations of PM_{2.5} emitted from the combustion of leaves from a broadleaf shrub.

Similarly, in a study aimed at determining the emission factors of PM_{2.5} emitted from stoves by combustion of maize straw and wheat straw, Sun et al., 2019 [121] found different amounts of mannitol and inositol in such biofuels.

Schmidl et al., 2008 [142] found sugar alcohols in notable concentrations in leaf burning samples, suggesting the use of polyols to identify the contribution of leaf burning to high organic matter levels in ambient air.

Besides mannitol, inositol and arabitol, glycerol, xylitol and erythritol are also found in atmospheric monitoring studies (Table S1). In particular, erythritol, commonly present in soil microbial metabolites, is produced when soil combustion occurs following the burning of agricultural waste in fields [184]. It has also been widely detected during monitoring analysis, in addition to xylitol and sorbitol [60,127,128,133,185,186].

4.3. Primary Sugars

In addition to the saccharide compounds mentioned above, several studies have revealed that mono- and disaccharides are relatively abundant water-soluble organic components of atmospheric aerosols [187]. For example, glucose has been used as a marker for vegetable materials (such as leaves and pollen) and soil emissions in several studies [43,58], and trehalose is commonly associated with microbial and fungal activity [188,189].

Hence, biogenic sources of monosaccharides mainly include microorganism, vascular plants and animals [144], soil and associated biota [32].

Monosaccharides are thought to be relatively stable in the atmosphere [34], although studies focused on their atmospheric lifetime and spatial distribution are still limited. Nevertheless, atmospheric concentrations of monosaccharides have been quantified in several studies on PM emissions in both rural and urban areas. For example, Nirmalkar et al., 2015 [133], through an environmental monitoring study at a rural site in central India, found high concentrations of trehalose in PM_{2.5}, attributing it to the thermal splitting of polysaccharides that occurs at high temperatures. Similarly, in a PM monitoring campaign in downtown Shanghai, Ren et al., 2020 [127] attributed the fraction composed of primary sugars (e.g., xylose, mannose, fructose, glucose, sucrose, maltose and trehalose, among others) to biomass burning. From this research emerged the possibility that anthropogenic emissions of primary sugars in the ambient air may occur by thermal stripping of cellulose during biomass burning events and be affected both by the type of fuel [190] and by the type of the combustion plant [191,192].

5. Conclusions

Publications worldwide agree on the identification of biomass burning as a major source of atmospheric particulate matter. The present work focused on literature findings concerning biomass burning emissions in order to provide better knowledge of saccharides tracers. As chemical and physical burning processes produce several compounds not attributable to other sources (e.g., fossil fuels), the detection of such specific markers is essential to evaluate the contribution of biomass burning to airborne particulate matter. A number of relevant mostly laboratory-based studies have contributed to our knowledge of the saccharide products of biomass combustion. Many of these studies have involved controlled pyrolysis of individual components or the burning of actual vegetation samples. Some characterization studies of smoke aerosols collected during field campaigns have also been carried out. By providing a picture of sugar compounds naturally and anthropologically emitted around the world, it is found that monosaccharide anhydrides, sugar alcohols and primary sugars have been widely reported as organic tracers for biomass burning. On the other hand, it has been demonstrated that emissions of such compounds depend not only on combustion characteristics and appliances but also on the type of biofuel and the

atmospheric conditions. Hence, it is not currently possible to define a single compound as a universal marker of biomass combustion. In this field, in order to help researchers to obtain an accurate and realistic attribution of saccharide sources of ambient PM, future studies might be oriented toward the monitoring of specific saccharides in source apportionment studies and the integration of local emission information and dispersion models, as they have not yet been sufficiently investigated.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/ijerph19074387/s1>, Table S1: Saccharide compounds identified in the research articles reviewed [193–197].

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References

1. Hong, Y.; Cao, F.; Fan, M.Y.; Lin, Y.C.; Gul, C.; Yu, M.; Wu, X.; Zhai, X.; Zhang, Y.L. Impacts of chemical degradation of levoglucosan on quantifying biomass burning contribution to carbonaceous aerosols: A case study in Northeast China. *Sci. Total Environ.* **2022**, *819*, 152007. [CrossRef] [PubMed]
2. Caumo, S.; Yera, A.B.; Vicente, A.; Alves, C.; Roubicek, D.A.; de Castro Vasconcellos, P. Particulate matter-bound organic compounds: Levels, mutagenicity, and health risks. *Environ. Sci. Pollut. Res.* **2022**, 1–18, Ahead of print. [CrossRef] [PubMed]
3. Olsson, P.Q.; Benner, R.L. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change by John, H. Seinfeld (California Institute of Technology) and Spyros, N. Pandis (Carnegie Mellon University). *J. Am. Chem. Soc.* **1999**, *121*, 1423. [CrossRef]
4. Pöschl, U. Atmospheric Aerosols: Composition, Transformation, Climate and Health Effects. *Angew. Chem. Int. Ed.* **2005**, *44*, 7520–7540. [CrossRef]
5. Calvo, A.I.; Alves, C.; Castro, A.; Pont, V.; Vicente, A.M.; Fraile, R. Research on aerosol sources and chemical composition: Past, current and emerging issues. *Atmos. Res.* **2013**, *120–121*, 1–28. [CrossRef]
6. Vicente, E.D.; Alves, C.A. An overview of particulate emissions from residential biomass combustion. *Atmos. Res.* **2018**, *199*, 159–185. [CrossRef]
7. He, L.; Zhang, J. Particulate matter (PM) oxidative potential: Measurement methods and links to PM physicochemical characteristics and health effects. *Crit. Rev. Environ. Sci. Technol.* **2022**, 1–21, Ahead of print. [CrossRef]
8. Samet, J.M.; Dominici, F.; Currier, F.C.; Coursac, I.; Zeger, S.L. Fine Particulate Air Pollution and Mortality in 20 U.S. Cities, 1987–1994. *N. Engl. J. Med.* **2000**, *343*, 1742–1749. [CrossRef]
9. Sigsgaard, T.; Forsberg, B.; Annesi-Maesano, I.; Blomberg, A.; Bølling, A.; Boman, C.; Bønløkke, J.; Brauer, M.; Bruce, N.; Héroux, M.-E.; et al. Health impacts of anthropogenic biomass burning in the developed world. *Eur. Respir. J.* **2015**, *46*, 1577–1588. [CrossRef]
10. Kocbach Bølling, A.; Pagels, J.; Yttri, K.E.; Barregard, L.; Sallsten, G.; Schwarze, P.E.; Boman, C. Health effects of residential wood smoke particles: The importance of combustion conditions and physicochemical particle properties. *Part. Fibre Toxicol.* **2009**, *6*, 29. [CrossRef]
11. Grantz, D.A.; Garner, J.H.B.; Johnson, D.W. Ecological effects of particulate matter. *Environ. Int.* **2003**, *29*, 213–239. [CrossRef]
12. Frosch, M.; Prisle, N.L.; Bilde, M.; Varga, Z.; Kiss, G. Joint effect of organic acids and inorganic salts on cloud droplet activation. *Atmos. Chem. Phys.* **2011**, *11*, 3895–3911. [CrossRef]
13. Kim, Y.J.; Kim, K.W.; Kim, S.D.; Lee, B.K.; Han, J.S. Fine particulate matter characteristics and its impact on visibility impairment at two urban sites in Korea: Seoul and Incheon. *Atmos. Environ.* **2006**, *40*, 593–605. [CrossRef]
14. Jimenez, J.L.; Canagaratna, M.R.; Donahue, N.M.; Prevot, A.S.H.; Zhang, Q.; Kroll, J.H.; DeCarlo, P.F.; Allan, J.D.; Coe, H.; Ng, N.L.; et al. Evolution of Organic Aerosols in the Atmosphere. *Science* **2009**, *326*, 1525–1529. [CrossRef] [PubMed]

15. Cao, J.; Wang, Q.; Chow, J.C.; Watson, J.G.; Tie, X.; Shen, Z.; Wang, P.; An, Z. Impacts of aerosol compositions on visibility impairment in Xi'an, China. *Atmos. Environ.* **2012**, *59*, 559–566. [[CrossRef](#)]
16. Streets, D.G.; Yarber, K.F.; Woo, J.-H.; Carmichael, G.R. Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions. *Glob. Biogeochem. Cycles* **2003**, *17*, 1–10. [[CrossRef](#)]
17. Aggarwal, S.G.; Kawamura, K. Carbonaceous and inorganic composition in long-range transported aerosols over northern Japan: Implication for aging of water-soluble organic fraction. *Atmos. Environ.* **2009**, *43*, 2532–2540. [[CrossRef](#)]
18. Wang, Z.; Bi, X.; Sheng, G.; Fu, J. Characterization of organic compounds and molecular tracers from biomass burning smoke in South China I: Broad-leaf trees and shrubs. *Atmos. Environ.* **2009**, *43*, 3096–3102. [[CrossRef](#)]
19. Rogge, W.F.; Hildemann, L.M.; Mazurek, M.A.; Cass, G.R. Sources of Fine Organic Aerosol. 9. Pine, Oak, and Synthetic Log Combustion in Residential Fireplaces. *Environ. Sci. Technol.* **1998**, *32*, 13–22. [[CrossRef](#)]
20. Paraskevopoulou, D.; Liakakou, E.; Gerasopoulos, E.; Mihalopoulos, N. Sources of atmospheric aerosol from long-term measurements (5years) of chemical composition in Athens, Greece. *Sci. Total Environ.* **2015**, *527*, 165–178. [[CrossRef](#)]
21. Viana, M.; Reche, C.; Amato, F.; Alastuey, A.; Querol, X.; Moreno, T.; Lucarelli, F.; Nava, S.; Calzolari, G.; Chiari, M.; et al. Evidence of biomass burning aerosols in the Barcelona urban environment during winter time. *Atmos. Environ.* **2013**, *72*, 81–88. [[CrossRef](#)]
22. Caseiro, A.; Bauer, H.; Schmidl, C.; Pio, C.A.; Puxbaum, H. Wood burning impact on PM10 in three Austrian regions. *Atmos. Environ.* **2009**, *43*, 2186–2195. [[CrossRef](#)]
23. Dambruoso, P.; de Gennaro, G.; Di Gilio, A.; Palmisani, J.; Tutino, M. The impact of infield biomass burning on PM levels and its chemical composition. *Environ. Sci. Pollut. Res.* **2014**, *21*, 13175–13185. [[CrossRef](#)] [[PubMed](#)]
24. Kostenidou, E.; Kaltsonoudis, C.; Tsimikiotou, M.; Louvaris, E.; Russell, L.M.; Pandis, S.N. Burning of olive tree branches: A major organic aerosol source in the Mediterranean. *Atmos. Chem. Phys.* **2013**, *13*, 8797–8811. [[CrossRef](#)]
25. Estrellan, C.R.; Iino, F. Toxic emissions from open burning. *Chemosphere* **2010**, *80*, 193–207. [[CrossRef](#)] [[PubMed](#)]
26. Demirbas, A. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. *Prog. Energy Combust. Sci.* **2005**, *31*, 171–192. [[CrossRef](#)]
27. Saidur, R.; Abdelaziz, E.A.; Demirbas, A.; Hossain, M.S.; Mekhilef, S. A review on biomass as a fuel for boilers. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2262–2289. [[CrossRef](#)]
28. Vincenti, B.; Proto, A.R.; Paris, E.; Palma, A.; Carnevale, M.; Guerriero, E.; Bernardini, F.; Tonolo, A.; Di Stefano, V.; Gallucci, F. Chemical and physical characterization of pellet composed of biomass of different essences. In Proceedings of the European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies, Virtual, Online, 6–9 July 2020; pp. 124–127.
29. Proto, A.R.; Palma, A.; Paris, E.; Papandrea, S.F.; Vincenti, B.; Carnevale, M.; Guerriero, E.; Bonofiglio, R.; Gallucci, F. Assessment of wood chip combustion and emission behavior of different agricultural biomasses. *Fuel* **2020**, *289*, 119758. [[CrossRef](#)]
30. Li, X.; Wang, S.; Duan, L.; Hao, J.; Nie, Y. Carbonaceous Aerosol Emissions from Household Biofuel Combustion in China. *Environ. Sci. Technol.* **2009**, *43*, 6076–6081. [[CrossRef](#)]
31. Wu, X.; Vu, T.V.; Shi, Z.; Harrison, R.M.; Liu, D.; Cen, K. Characterization and source apportionment of carbonaceous PM2.5 particles in China—A review. *Atmos. Environ.* **2018**, *189*, 187–212. [[CrossRef](#)]
32. Marynowski, L.; Simoneit, B.R.T. Saccharides in atmospheric particulate and sedimentary organic matter: Status overview and future perspectives. *Chemosphere* **2021**, *288*, 132376. [[CrossRef](#)]
33. Yan, C.; Sullivan, A.P.; Cheng, Y.; Zheng, M.; Zhang, Y.; Zhu, T.; Collett, J.L. Characterization of saccharides and associated usage in determining biogenic and biomass burning aerosols in atmospheric fine particulate matter in the North China Plain. *Sci. Total Environ.* **2019**, *650*, 2939–2950. [[CrossRef](#)] [[PubMed](#)]
34. Wang, X.; Shen, Z.; Liu, F.; Lu, D.; Tao, J.; Lei, Y.; Zhang, Q.; Zeng, Y.; Xu, H.; Wu, Y.; et al. Saccharides in summer and winter PM2.5 over Xi'an, Northwestern China: Sources, and yearly variations of biomass burning contribution to PM2.5. *Atmos. Res.* **2018**, *214*, 410–417. [[CrossRef](#)]
35. Jia, Y.; Bhat, S.; Fraser, M.P. Characterization of saccharides and other organic compounds in fine particles and the use of saccharides to track primary biologically derived carbon sources. *Atmos. Environ.* **2010**, *44*, 724–732. [[CrossRef](#)]
36. Wang, G.; Chen, C.; Li, J.; Zhou, B.; Xie, M.; Hu, S.; Kawamura, K.; Chen, Y. Molecular composition and size distribution of sugars, sugar-alcohols and carboxylic acids in airborne particles during a severe urban haze event caused by wheat straw burning. *Atmos. Environ.* **2011**, *45*, 2473–2479. [[CrossRef](#)]
37. Schauer, J.J.; Rogge, W.F.; Hildemann, L.M.; Mazurek, M.A.; Cass, G.R.; Simoneit, B.R.T. Source apportionment of airborne particulate matter using organic compounds as tracers. *Atmos. Environ.* **1996**, *30*, 3837–3855. [[CrossRef](#)]
38. Alvi, M.U.; Kistler, M.; Shahid, I.; Alam, K.; Chishtie, F.; Mahmud, T.; Kasper-Giebl, A. Composition and source apportionment of saccharides in aerosol particles from an agro-industrial zone in the Indo-Gangetic Plain. *Environ. Sci. Pollut. Res.* **2020**, *27*, 14124–14137. [[CrossRef](#)]
39. Aguilera, J.; Whigham, L.D. Using the 13C/12C carbon isotope ratio to characterise the emission sources of airborne particulate matter: A review of literature. *Isotopes Environ. Health Stud.* **2018**, *54*, 573–587. [[CrossRef](#)] [[PubMed](#)]
40. Islam, M.R.; Jayarathne, T.; Simpson, I.J.; Werden, B.; Maben, J.; Gilbert, A.; Praveen, P.S.; Adhikari, S.; Panday, A.K.; Rupakheti, M.; et al. Ambient air quality in the Kathmandu Valley, Nepal, during the pre-monsoon: Concentrations and sources of particulate matter and trace gases. *Atmos. Chem. Phys.* **2020**, *20*, 2927–2951. [[CrossRef](#)]
41. Maffia, J.; Dinuccio, E.; Amon, B.; Balsari, P. PM emissions from open field crop management: Emission factors, assessment methods and mitigation measures—A review. *Atmos. Environ.* **2020**, *226*, 117381. [[CrossRef](#)]

42. Shahid, I.; Kistler, M.; Mukhtar, A.; Ramirez-Santa Cruz, C.; Bauer, H.; Puxbaum, H. Chemical composition of particles from traditional burning of Pakistani wood species. *Atmos. Environ.* **2014**, *121*, 35–41. [[CrossRef](#)]
43. Zangrando, R.; Barbaro, E.; Kirchgeorg, T.; Vecchiato, M.; Scalabrin, E.; Radaelli, M.; Đorđević, D.; Barbante, C.; Gambaro, A. Five primary sources of organic aerosols in the urban atmosphere of Belgrade (Serbia). *Sci. Total Environ.* **2016**, *571*, 1441–1453. [[CrossRef](#)] [[PubMed](#)]
44. Scaramboni, C.; Urban, R.C.; Lima-Souza, M.; Nogueira, R.F.P.; Cardoso, A.A.; Allen, A.G.; Campos, M.L.A.M. Total sugars in atmospheric aerosols: An alternative tracer for biomass burning. *Atmos. Environ.* **2015**, *100*, 185–192. [[CrossRef](#)]
45. Harrison, M.A.J.; Barra, S.; Borghesi, D.; Vione, D.; Arsene, C.; Iulian Olariu, R. Nitrated phenols in the atmosphere: A review. *Atmos. Environ.* **2005**, *39*, 231–248. [[CrossRef](#)]
46. Vincenti, B.; Paris, E.; Palma, A.; Carnevale, M.; Manganiello, R.; Salerno, M.; Borello, D.; Guerriero, E.; Colantoni, A.; Tonolo, A.; et al. Characterization of biomass burning tracers in PM 2.5 aerosols. In Proceedings of the European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies, Virtual, Online, 26–29 April 2021; pp. 1165–1167.
47. Kasischke, E.S.; Penner, J.E. Improving global estimates of atmospheric emissions from biomass burning. *J. Geophys. Res. Atmos.* **2004**, *109*, 1–9. [[CrossRef](#)]
48. Voulgarakis, A.; Marlier, M.E.; Faluvegi, G.; Shindell, D.T.; Tsigaridis, K.; Mangeon, S. Interannual variability of tropospheric trace gases and aerosols: The role of biomass burning emissions. *J. Geophys. Res. Atmos.* **2015**, *120*, 7157–7173. [[CrossRef](#)]
49. Keywood, M.; Kanakidou, M.; Stohl, A.; Dentener, F.; Grassi, G.; Meyer, C.P.; Torseth, K.; Edwards, D.; Thompson, A.M.; Lohmann, U.; et al. Fire in the Air: Biomass Burning Impacts in a Changing Climate. *Crit. Rev. Environ. Sci. Technol.* **2013**, *43*, 40–83. [[CrossRef](#)]
50. Louchouart, P.; Kuo, L.-J.; Wade, T.L.; Schantz, M. Determination of levoglucosan and its isomers in size fractions of aerosol standard reference materials. *Atmos. Environ.* **2009**, *43*, 5630–5636. [[CrossRef](#)]
51. Fabbri, D.; Torri, C.; Simoneit, B.R.T.; Marynowski, L.; Rushdi, A.I.; Fabiańska, M.J. Levoglucosan and other cellulose and lignin markers in emissions from burning of Miocene lignites. *Atmos. Environ.* **2009**, *43*, 2286–2295. [[CrossRef](#)]
52. Hsu, C.-L.; Cheng, C.-Y.; Lee, C.-T.; Ding, W.-H. Derivatization procedures and determination of levoglucosan and related monosaccharide anhydrides in atmospheric aerosols by gas chromatography–mass spectrometry. *Talanta* **2007**, *72*, 199–205. [[CrossRef](#)] [[PubMed](#)]
53. Jia, Y.; Fraser, M. Characterization of Saccharides in Size-fractionated Ambient Particulate Matter and Aerosol Sources: The Contribution of Primary Biological Aerosol Particles (PBAPs) and Soil to Ambient Particulate Matter. *Environ. Sci. Technol.* **2011**, *45*, 930–936. [[CrossRef](#)]
54. Bauer, H.; Claeys, M.; Vermeylen, R.; Schueller, E.; Weinke, G.; Berger, A.; Puxbaum, H. Arabitol and mannitol as tracers for the quantification of airborne fungal spores. *Atmos. Environ.* **2008**, *42*, 588–593. [[CrossRef](#)]
55. Alves, C.A.; Vicente, A.; Monteiro, C.; Gonçalves, C.; Evtyugina, M.; Pio, C. Emission of trace gases and organic components in smoke particles from a wildfire in a mixed-evergreen forest in Portugal. *Sci. Total Environ.* **2011**, *409*, 1466–1475. [[CrossRef](#)]
56. Alves, C.A.; Gonçalves, C.; Evtyugina, M.; Pio, C.A.; Mirante, F.; Puxbaum, H. Particulate organic compounds emitted from experimental wildland fires in a Mediterranean ecosystem. *Atmos. Environ.* **2010**, *44*, 2750–2759. [[CrossRef](#)]
57. Graham, B.; Mayol-Bracero, O.L.; Guyon, P.; Roberts, G.C.; Decesari, S.; Facchini, M.C.; Artaxo, P.; Maenhaut, W.; Köll, P.; Andreae, M.O. Water-soluble organic compounds in biomass burning aerosols over Amazonia 1. Characterization by NMR and GC-MS. *J. Geophys. Res. Atmos.* **2002**, *107*, 1–16. [[CrossRef](#)]
58. Nirmalkar, J.; Deshmukh, D.K.; Deb, M.K.; Tsai, Y.I.; Pervez, S. Characteristics of aerosol during major biomass burning events over eastern central India in winter: A tracer-based approach. *Atmos. Pollut. Res.* **2019**, *10*, 817–826. [[CrossRef](#)]
59. Li, X.; Liu, Y.; Li, D.; Wang, G.; Bai, Y.; Diao, H.; Shen, R.; Hu, B.; Xin, J.; Liu, Z.; et al. Molecular composition of organic aerosol over an agricultural site in North China Plain: Contribution of biogenic sources to PM_{2.5}. *Atmos. Environ.* **2017**, *164*, 448–457. [[CrossRef](#)]
60. Zhao, Y.; Ren, H.; Deng, J.; Li, L.; Hu, W.; Ren, L.; Yue, S.; Fan, Y.; Wu, L.; Li, J.; et al. High daytime abundance of primary organic aerosols over Mt. Emei, Southwest China in summer. *Sci. Total Environ.* **2020**, *703*, 134475. [[CrossRef](#)]
61. Thepnuan, D.; Chantara, S.; Lee, C.-T.; Lin, N.H.; Tsai, Y.I. Molecular markers for biomass burning associated with the characterization of PM_{2.5} and component sources during dry season haze episodes in Upper South East Asia. *Sci. Total Environ.* **2019**, *658*, 708–722. [[CrossRef](#)] [[PubMed](#)]
62. Pietrogrande, M.C.; Bacco, D.; Visentin, M.; Ferrari, S.; Poluzzi, V. Polar organic marker compounds in atmospheric aerosol in the Po Valley during the Supersito campaigns—Part 1: Low molecular weight carboxylic acids in cold seasons. *Atmos. Environ.* **2014**, *86*, 164–175. [[CrossRef](#)]
63. Graham, B.; Guyon, P.; Taylor, P.E.; Artaxo, P.; Maenhaut, W.; Glovsky, M.M.; Flagan, R.C.; Andreae, M.O. Organic compounds present in the natural Amazonian aerosol: Characterization by gas chromatography–mass spectrometry. *J. Geophys. Res. Atmos.* **2003**, *108*, 1–13. [[CrossRef](#)]
64. Titos, G.; del Águila, A.; Cazorla, A.; Lyamani, H.; Casquero-Vera, J.A.; Colombi, C.; Cuccia, E.; Gianelle, V.; Močnik, G.; Alastuey, A.; et al. Spatial and temporal variability of carbonaceous aerosols: Assessing the impact of biomass burning in the urban environment. *Sci. Total Environ.* **2017**, *578*, 613–625. [[CrossRef](#)] [[PubMed](#)]
65. Charlson, R.J.; Schwartz, S.E.; Hales, J.M.; Cess, R.D.; Coakley, J.A.; Hansen, J.E.; Hofmann, D.J. Climate Forcing by Anthropogenic Aerosols. *Science* **1992**, *255*, 423–430. [[CrossRef](#)] [[PubMed](#)]

66. Crutzen, P.J.; Andreae, M.O. Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biogeochemical Cycles. *Science* **1990**, *250*, 1669–1678. [[CrossRef](#)] [[PubMed](#)]
67. Khalil, M.A.K.; Rasmussen, R.A. Tracers of wood smoke. *Atmos. Environ.* **2003**, *37*, 1211–1222. [[CrossRef](#)]
68. Eriksson, A.C.; Nordin, E.Z.; Nyström, R.; Pettersson, E.; Swietlicki, E.; Bergvall, C.; Westerholm, R.; Boman, C.; Pagels, J.H. Particulate PAH Emissions from Residential Biomass Combustion: Time-Resolved Analysis with Aerosol Mass Spectrometry. *Environ. Sci. Technol.* **2014**, *48*, 7143–7150. [[CrossRef](#)]
69. Jordan, T.B.; Seen, A.J. Effect of Airflow Setting on the Organic Composition of Woodheater Emissions. *Environ. Sci. Technol.* **2005**, *39*, 3601–3610. [[CrossRef](#)]
70. Lamberg, H.; Nuutinen, K.; Tissari, J.; Ruusunen, J.; Yli-Pirilä, P.; Sippula, O.; Tapanainen, M.; Jalava, P.; Makkonen, U.; Teinilä, K.; et al. Physicochemical characterization of fine particles from small-scale wood combustion. *Atmos. Environ.* **2011**, *45*, 7635–7643. [[CrossRef](#)]
71. Leskinen, J.; Tissari, J.; Uski, O.; Virén, A.; Torvela, T.; Kaivosoja, T.; Lamberg, H.; Nuutinen, I.; Kettunen, T.; Joutsensaari, J.; et al. Fine particle emissions in three different combustion conditions of a wood chip-fired appliance—Particulate physico-chemical properties and induced cell death. *Atmos. Environ.* **2014**, *86*, 129–139. [[CrossRef](#)]
72. Vicente, E.D.; Duarte, M.A.; Calvo, A.I.; Nunes, T.F.; Tarelho, L.A.C.; Custódio, D.; Colombi, C.; Gianelle, V.; Sanchez de la Campa, A.; Alves, C.A. Influence of operating conditions on chemical composition of particulate matter emissions from residential combustion. *Atmos. Res.* **2015**, *166*, 92–100. [[CrossRef](#)]
73. Vicente, E.D.; Duarte, M.A.; Tarelho, L.A.C.; Nunes, T.F.; Amato, F.; Querol, X.; Colombi, C.; Gianelle, V.; Alves, C.A. Particulate and gaseous emissions from the combustion of different biofuels in a pellet stove. *Atmos. Environ.* **2015**, *120*, 15–27. [[CrossRef](#)]
74. Vicente, E.D.; Vicente, A.M.; Musa Bandowe, B.A.; Alves, C.A. Particulate phase emission of parent polycyclic aromatic hydrocarbons (PAHs) and their derivatives (alkyl-PAHs, oxygenated-PAHs, azaarenes and nitrated PAHs) from manually and automatically fired combustion appliances. *Air Qual. Atmos. Health* **2016**, *9*, 653–668. [[CrossRef](#)]
75. Andreae, M.O. Soot carbon and excess fine potassium: Long-range transport of combustion-derived aerosols. *Science* **1983**, *220*, 1148–1151. [[CrossRef](#)] [[PubMed](#)]
76. Cao, F.; Zhang, S.-C.; Kawamura, K.; Zhang, Y.-L. Inorganic markers, carbonaceous components and stable carbon isotope from biomass burning aerosols in Northeast China. *Sci. Total Environ.* **2016**, *572*, 1244–1251. [[CrossRef](#)]
77. Cheng, Y.; Engling, G.; He, K.B.; Duan, F.K.; Ma, Y.L.; Du, Z.Y.; Liu, J.M.; Zheng, M.; Weber, R.J. Biomass burning contribution to Beijing aerosol. *Atmos. Chem. Phys.* **2013**, *13*, 7765–7781. [[CrossRef](#)]
78. Urban, R.C.; Lima-Souza, M.; Caetano-Silva, L.; Queiroz, M.E.C.; Nogueira, R.F.P.; Allen, A.G.; Cardoso, A.A.; Held, G.; Campos, M.L.A.M. Use of levoglucosan, potassium, and water-soluble organic carbon to characterize the origins of biomass-burning aerosols. *Atmos. Environ.* **2012**, *61*, 562–569. [[CrossRef](#)]
79. Giannoni, M.; Martellini, T.; Del Bubba, M.; Gambaro, A.; Zangrando, R.; Chiari, M.; Lepri, L.; Cincinelli, A. The use of levoglucosan for tracing biomass burning in PM_{2.5} samples in Tuscany (Italy). *Environ. Pollut.* **2012**, *167*, 7–15. [[CrossRef](#)]
80. Olmez, I.; Sheffield, A.E.; Gordon, G.E.; Houck, J.E.; Pritchett, L.C.; Cooper, J.A.; Dzubay, T.G.; Bennett, R.L. Compositions of Particles from Selected Sources in Philadelphia for Receptor Modeling Applications. *JAPCA* **1988**, *38*, 1392–1402. [[CrossRef](#)]
81. Sheffield, A.E.; Gordon, G.E.; Currie, L.A.; Riederer, G.E. Organic, elemental, and isotopic tracers of air pollution sources in Albuquerque, NM. *Atmos. Environ.* **1994**, *28*, 1371–1384. [[CrossRef](#)]
82. Schauer, J.J.; Kleeman, M.J.; Cass, G.R.; Simoneit, B.R.T. Measurement of Emissions from Air Pollution Sources. 1. C₁ through C₂₉ Organic Compounds from Meat Charbroiling. *Environ. Sci. Technol.* **1999**, *33*, 1566–1577. [[CrossRef](#)]
83. Simoneit, B.R.T.; Schauer, J.J.; Nolte, C.G.; Oros, D.R.; Elias, V.O.; Fraser, M.P.; Rogge, W.F.; Cass, G.R. Levoglucosan, a tracer for cellulose in biomass burning and atmospheric particles. *Atmos. Environ.* **1999**, *33*, 173–182. [[CrossRef](#)]
84. Cordell, R.L.; Mazet, M.; Dechoux, C.; Hama, S.M.L.; Staelens, J.; Hofman, J.; Stroobants, C.; Roekens, E.; Kos, G.P.A.; Weijers, E.P.; et al. Evaluation of biomass burning across North West Europe and its impact on air quality. *Atmos. Environ.* **2016**, *141*, 276–286. [[CrossRef](#)]
85. Rybicki, M.; Marynowski, L.; Bechtel, A.; Simoneit, B.R.T. Variations in $\delta^{13}\text{C}$ values of levoglucosan from low-temperature burning of lignite and biomass. *Sci. Total Environ.* **2020**, *733*, 138991. [[CrossRef](#)]
86. Yan, C.; Zheng, M.; Bosch, C.; Andersson, A.; Desyaterik, Y.; Sullivan, A.P.; Collett, J.L.; Zhao, B.; Wang, S.; He, K.; et al. Important fossil source contribution to brown carbon in Beijing during winter. *Sci. Rep.* **2017**, *7*, 43182. [[CrossRef](#)] [[PubMed](#)]
87. Górka, M.; Rybicki, M.; Simoneit, B.R.T.; Marynowski, L. Determination of multiple organic matter sources in aerosol PM₁₀ from Wrocław, Poland using molecular and stable carbon isotope compositions. *Atmos. Environ.* **2014**, *89*, 739–748. [[CrossRef](#)]
88. Lubecki, L.; Oen, A.M.P.; Breedveld, G.D.; Zamojska, A. Vertical profiles of sedimentary polycyclic aromatic hydrocarbons and black carbon in the Gulf of Gdańsk (Poland) and Oslofjord/Drammensfjord (Norway), and their relation to regional energy transitions. *Sci. Total Environ.* **2019**, *646*, 336–346. [[CrossRef](#)]
89. Marynowski, L.; Bucha, M.; Smolarek, J.; Wendorff, M.; Simoneit, B.R.T. Occurrence and significance of mono-, di- and anhydrosaccharide biomolecules in Mesozoic and Cenozoic lignites and fossil wood. *Org. Geochem.* **2018**, *116*, 13–22. [[CrossRef](#)]
90. Rybicki, M.; Marynowski, L.; Simoneit, B.R.T. Composition of organic compounds from low-temperature burning of lignite and their application as tracers in ambient air. *Chemosphere* **2020**, *249*, 126087. [[CrossRef](#)]
91. Balasubramanian, R.; Qian, W.-B.; Decesari, S.; Facchini, M.C.; Fuzzi, S. Comprehensive characterization of PM_{2.5} aerosols in Singapore. *J. Geophys. Res. Atmos.* **2003**, *108*, 4523. [[CrossRef](#)]

92. Kiely, L.; Spracklen, D.V.; Wiedinmyer, C.; Conibear, L.; Reddington, C.L.; Archer-Nicholls, S.; Lowe, D.; Arnold, S.R.; Knote, C.; Khan, M.F.; et al. New estimate of particulate emissions from Indonesian peat fires in 2015. *Atmos. Chem. Phys.* **2019**, *19*, 11105–11121. [[CrossRef](#)]
93. Cai, S.; Ma, Q.; Wang, S.; Zhao, B.; Brauer, M.; Cohen, A.; Martin, R.V.; Zhang, Q.; Li, Q.; Wang, Y.; et al. Impact of air pollution control policies on future PM_{2.5} concentrations and their source contributions in China. *J. Environ. Manag.* **2018**, *227*, 124–133. [[CrossRef](#)] [[PubMed](#)]
94. Lai, A.M.; Carter, E.; Shan, M.; Ni, K.; Clark, S.; Ezzati, M.; Wiedinmyer, C.; Yang, X.; Baumgartner, J.; Schauer, J.J. Chemical composition and source apportionment of ambient, household, and personal exposures to PM_{2.5} in communities using biomass stoves in rural China. *Sci. Total Environ.* **2019**, *646*, 309–319. [[CrossRef](#)] [[PubMed](#)]
95. Maykut, N.N.; Lewtas, J.; Kim, E.; Larson, T.V. Source Apportionment of PM_{2.5} at an Urban IMPROVE Site in Seattle, Washington. *Environ. Sci. Technol.* **2003**, *37*, 5135–5142. [[CrossRef](#)]
96. Winchester, J.W.; Nifong, G.D. Water pollution in Lake Michigan by trace elements from pollution aerosol fallout. *Water. Air. Soil Pollut.* **1971**, *1*, 50–64. [[CrossRef](#)]
97. Zoller, W.H.; Gladney, E.S.; Duce, R.A. Atmospheric Concentrations and Sources of Trace Metals at the South Pole. *Science* **1974**, *183*, 198–200. [[CrossRef](#)]
98. Zhang, K.; Shang, X.; Herrmann, H.; Meng, F.; Mo, Z.; Chen, J.; Lv, W. Approaches for identifying PM_{2.5} source types and source areas at a remote background site of South China in spring. *Sci. Total Environ.* **2019**, *691*, 1320–1327. [[CrossRef](#)] [[PubMed](#)]
99. Paatero, P. Least squares formulation of robust non-negative factor analysis. *Chemom. Intell. Lab. Syst.* **1997**, *37*, 23–35. [[CrossRef](#)]
100. Paatero, P. The Multilinear Engine—A Table-Driven, Least Squares Program for Solving Multilinear Problems, Including the n-Way Parallel Factor Analysis Model. *J. Comput. Graph. Stat.* **1999**, *8*, 854–888. [[CrossRef](#)]
101. Choi, J.K.; Ban, S.J.; Kim, Y.P.; Kim, Y.H.; Yi, S.M.; Zoh, K.D. Molecular marker characterization and source appointment of particulate matter and its organic aerosols. *Chemosphere* **2015**, *134*, 482–491. [[CrossRef](#)]
102. Jaeckels, J.M.; Bae, M.-S.; Schauer, J.J. Positive Matrix Factorization (PMF) Analysis of Molecular Marker Measurements to Quantify the Sources of Organic Aerosols. *Environ. Sci. Technol.* **2007**, *41*, 5763–5769. [[CrossRef](#)]
103. Belis, C.A.; Karagulian, F.; Larsen, B.R.; Hopke, P.K. Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe. *Atmos. Environ.* **2013**, *69*, 94–108. [[CrossRef](#)]
104. Hopke, P.K. Review of receptor modeling methods for source apportionment. *J. Air Waste Manag. Assoc.* **2016**, *66*, 237–259. [[CrossRef](#)] [[PubMed](#)]
105. Reff, A.; Eberly, S.I.; Bhave, P. V Receptor Modeling of Ambient Particulate Matter Data Using Positive Matrix Factorization: Review of Existing Methods. *J. Air Waste Manag. Assoc.* **2007**, *57*, 146–154. [[CrossRef](#)] [[PubMed](#)]
106. Watson, J.G.; Chow, J.C.; Fujita, E.M. Review of volatile organic compound source apportionment by chemical mass balance. *Atmos. Environ.* **2001**, *35*, 1567–1584. [[CrossRef](#)]
107. Maenhaut, W.; Vermeylen, R.; Claeys, M.; Vercauteren, J.; Matheeuissen, C.; Roekens, E. Assessment of the contribution from wood burning to the PM₁₀ aerosol in Flanders, Belgium. *Sci. Total Environ.* **2012**, *437*, 226–236. [[CrossRef](#)]
108. Puxbaum, H.; Caseiro, A.; Sánchez-Ochoa, A.; Kasper-Giebl, A.; Claeys, M.; Gelencsér, A.; Legrand, M.; Preunkert, S.; Pio, C.A. Levoglucosan levels at background sites in Europe for assessing the impact of biomass combustion on the European aerosol background. *J. Geophys. Res. Atmos.* **2007**, *112*. [[CrossRef](#)]
109. Pashynska, V.; Vermeylen, R.; Vas, G.; Maenhaut, W.; Claeys, M. Development of a gas chromatographic/ion trap mass spectrometric method for the determination of levoglucosan and saccharidic compounds in atmospheric aerosols. Application to urban aerosols. *J. Mass Spectrom.* **2002**, *37*, 1249–1257. [[CrossRef](#)]
110. Piazzalunga, A.; Belis, C.; Bernardoni, V.; Cazzuli, O.; Fermo, P.; Valli, G.; Vecchi, R. Estimates of wood burning contribution to PM by the macro-tracer method using tailored emission factors. *Atmos. Environ.* **2011**, *45*, 6642–6649. [[CrossRef](#)]
111. Ribeiro, I.O.; do Santos, E.O.; Batista, C.E.; Fernandes, K.S.; Ye, J.; Medeiros, A.S.; e Oliveira, R.L.; de Sá, S.S.; de Sousa, T.R.; Kayano, M.T.; et al. Impact of biomass burning on a metropolitan area in the Amazon during the 2015 El Niño: The enhancement of carbon monoxide and levoglucosan concentrations. *Environ. Pollut.* **2020**, *260*, 114029. [[CrossRef](#)]
112. Sevimoğlu, O.; Rogge, W.F. Seasonal variations of PM₁₀—Trace elements, PAHs and Levoglucosan: Rural sugarcane growing area versus coastal urban area in Southeastern Florida, USA. Part II: Elemental concentrations. *Particuology* **2019**, *46*, 99–108. [[CrossRef](#)]
113. Parvin, F.; Seki, O.; Fujita, K.; Iizuka, Y.; Matoba, S.; Ando, T.; Sawada, K. Assessment for paleoclimatic utility of biomass burning tracers in SE-Dome ice core, Greenland. *Atmos. Environ.* **2019**, *196*, 86–94. [[CrossRef](#)]
114. Jayarathne, T.; Stockwell, C.E.; Gilbert, A.A.; Daugherty, K.; Cochrane, M.A.; Ryan, K.C.; Putra, E.I.; Saharjo, B.H.; Nurhayati, A.D.; Albar, I.; et al. Chemical characterization of fine particulate matter emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño. *Atmos. Chem. Phys.* **2018**, *18*, 2585–2600. [[CrossRef](#)]
115. Fujii, Y.; Mahmud, M.; Tohno, S.; Okuda, T.; Mizohata, A. A Case Study of PM_{2.5} Characterization in Bangi, Selangor, Malaysia during the Southwest Monsoon Season. *Aerosol Air Qual. Res.* **2016**, *16*, 2685–2691. [[CrossRef](#)]
116. Fujii, Y.; Iriana, W.; Oda, M.; Puriwigati, A.; Tohno, S.; Lestari, P.; Mizohata, A.; Huboyo, H.S. Characteristics of carbonaceous aerosols emitted from peatland fire in Riau, Sumatra, Indonesia. *Atmos. Environ.* **2014**, *87*, 164–169. [[CrossRef](#)]
117. Fujii, Y.; Tohno, S.; Amil, N.; Latif, M.T. Quantitative assessment of source contributions to PM_{2.5} on the west coast of Peninsular Malaysia to determine the burden of Indonesian peatland fire. *Atmos. Environ.* **2017**, *171*, 111–117. [[CrossRef](#)]

118. Tham, J.; Sarkar, S.; Jia, S.; Reid, J.S.; Mishra, S.; Sudiana, I.M.; Swarup, S.; Ong, C.N.; Yu, L.E. Impacts of peat-forest smoke on urban PM_{2.5} in the Maritime Continent during 2012–2015: Carbonaceous profiles and indicators. *Environ. Pollut.* **2019**, *248*, 496–505. [[CrossRef](#)]
119. Bukowiecki, N.; Steinbacher, M.; Henne, S.; Nguyen, N.A.; Nguyen, X.A.; Le Hoang, A.; Nguyen, D.L.; Duong, H.L.; Engling, G.; Wehrle, G.; et al. Effect of Large-scale Biomass Burning on Aerosol Optical Properties at the GAW Regional Station Pha Din, Vietnam. *Aerosol Air Qual. Res.* **2019**, *19*, 1172–1187. [[CrossRef](#)]
120. Schmidl, C.; Marr, I.L.; Caseiro, A.; Kotianová, P.; Berner, A.; Bauer, H.; Kasper-Giebl, A.; Puxbaum, H. Chemical characterisation of fine particle emissions from wood stove combustion of common woods growing in mid-European Alpine regions. *Atmos. Environ.* **2008**, *42*, 126–141. [[CrossRef](#)]
121. Sun, J.; Shen, Z.; Zhang, Y.; Zhang, Q.; Lei, Y.; Huang, Y.; Niu, X.; Xu, H.; Cao, J.; Ho, S.S.H.; et al. Characterization of PM_{2.5} source profiles from typical biomass burning of maize straw, wheat straw, wood branch, and their processed products (briquette and charcoal) in China. *Atmos. Environ.* **2019**, *205*, 36–45. [[CrossRef](#)]
122. Chantara, S.; Thepnuan, D.; Wiriya, W.; Prawan, S.; Tsai, Y.I. Emissions of pollutant gases, fine particulate matters and their significant tracers from biomass burning in an open-system combustion chamber. *Chemosphere* **2019**, *224*, 407–416. [[CrossRef](#)]
123. Zhang, T.; Engling, G.; Chan, C.Y.; Zhang, Y.N.; Zhang, Z.S.; Lin, M.; Sang, X.F.; Li, Y.D.; Li, Y.S. Contribution of fungal spores to particulate matter in a tropical rainforest. *Environ. Res. Lett.* **2010**, *5*, 024010. [[CrossRef](#)]
124. Jia, Y.; Clements, A.L.; Fraser, M.P. Saccharide composition in atmospheric particulate matter in the southwest US and estimates of source contributions. *J. Aerosol Sci.* **2010**, *41*, 62–73. [[CrossRef](#)]
125. Alves, C.; Rienda, I.C.; Vicente, A.; Vicente, E.; Gonçalves, C.; Candeias, C.; Rocha, F.; Lucarelli, F.; Pazzi, G.; Kováts, N.; et al. Morphological properties, chemical composition, cancer risks and toxicological potential of airborne particles from traffic and urban background sites. *Atmos. Res.* **2021**, *264*. [[CrossRef](#)]
126. Urban, R.C.; Alves, C.A.; Allen, A.G.; Cardoso, A.A.; Campos, M.L.A.M. Organic aerosols in a Brazilian agro-industrial area: Speciation and impact of biomass burning. *Atmos. Res.* **2016**, *169*, 271–279. [[CrossRef](#)]
127. Ren, G.; Yan, X.; Ma, Y.; Qiao, L.; Chen, Z.; Xin, Y.; Zhou, M.; Shi, Y.; Zheng, K.; Zhu, S.; et al. Characteristics and source apportionment of PM_{2.5}-bound saccharides and carboxylic acids in Central Shanghai, China. *Atmos. Res.* **2020**, *237*, 104817. [[CrossRef](#)]
128. Pietrogrande, M.C.; Bacco, D.; Visentin, M.; Ferrari, S.; Casali, P. Polar organic marker compounds in atmospheric aerosol in the Po Valley during the Supersito campaigns—Part 2: Seasonal variations of sugars. *Atmos. Environ.* **2014**, *97*, 215–225. [[CrossRef](#)]
129. Zhu, C.; Kawamura, K.; Kunwar, B. Organic tracers of primary biological aerosol particles at subtropical Okinawa Island in the western North Pacific Rim. *J. Geophys. Res. Atmos.* **2015**, *120*, 5504–5523. [[CrossRef](#)]
130. Fine, P.M.; Cass, G.R.; Simoneit, B.R.T. Chemical characterization of fine particle emissions from the wood stove combustion of prevalent united states tree species. *Environ. Eng. Sci.* **2004**, *21*, 705–721. [[CrossRef](#)]
131. Fu, P.; Kawamura, K.; Kobayashi, M.; Simoneit, B.R.T. Seasonal variations of sugars in atmospheric particulate matter from Gosan, Jeju Island: Significant contributions of airborne pollen and Asian dust in spring. *Atmos. Environ.* **2012**, *55*, 234–239. [[CrossRef](#)]
132. Emygdio, A.P.M.; Andrade, M.D.F.; Gonçalves, F.L.T.; Engling, G.; Zanetti, R.H.D.S.; Kumar, P. Biomarkers as indicators of fungal biomass in the atmosphere of São Paulo, Brazil. *Sci. Total Environ.* **2018**, *612*, 809–821. [[CrossRef](#)]
133. Nirmalkar, J.; Deshmukh, D.K.; Deb, M.K.; Tsai, Y.I.; Sopajaree, K. Mass loading and episodic variation of molecular markers in PM_{2.5} aerosols over a rural area in eastern central India. *Atmos. Environ.* **2015**, *117*, 41–50. [[CrossRef](#)]
134. Li, X.; Jiang, L.; Hoa, L.P.; Lyu, Y.; Xu, T.; Yang, X.; Iinuma, Y.; Chen, J.; Herrmann, H. Size distribution of particle-phase sugar and nitrophenol tracers during severe urban haze episodes in Shanghai. *Atmos. Environ.* **2016**, *145*, 115–127. [[CrossRef](#)]
135. Li, X.; Chen, M.; Le, H.P.; Wang, F.; Guo, Z.; Iinuma, Y.; Chen, J.; Herrmann, H. Atmospheric outflow of PM_{2.5} saccharides from megacity Shanghai to East China Sea: Impact of biological and biomass burning sources. *Atmos. Environ.* **2016**, *143*, 1–14. [[CrossRef](#)]
136. Yttri, K.E.; Dye, C.; Kiss, G. Ambient aerosol concentrations of sugars and sugar-alcohols at four different sites in Norway. *Atmos. Chem. Phys.* **2007**, *7*, 4267–4279. [[CrossRef](#)]
137. Lehmann, E. Sergejew, A.S. Chemie des Holzes und der Cellulose. Dresden und Leipzig 1959: Th. Steinkopff. VIII + 143 S. Übersetzt von H. Schwarz, Oberförster a. D. *Z. Pflanz. Düngung Bodenkd.* **1959**, *87*, 77–78. [[CrossRef](#)]
138. Simoneit, B.R.T.; Rogge, W.F.; Mazurek, M.A.; Standley, L.J.; Hildemann, L.M.; Cass, G.R. Lignin pyrolysis products, lignans, and resin acids as specific tracers of plant classes in emissions from biomass combustion. *Environ. Sci. Technol.* **1993**, *27*, 2533–2541. [[CrossRef](#)]
139. Roberts, A.F. A review of kinetics data for the pyrolysis of wood and related substances. *Combust. Flame* **1970**, *14*, 261–272. [[CrossRef](#)]
140. Shafizadeh, F. Pyrolysis and Combustion of Cellulosic Materials. *Adv. Carbohydr. Chem.* **1968**, *23*, 419–474. [[CrossRef](#)]
141. Bhattarai, H.; Saikawa, E.; Wan, X.; Zhu, H.; Ram, K.; Gao, S.; Kang, S.; Zhang, Q.; Zhang, Y.; Wu, G.; et al. Levoglucosan as a tracer of biomass burning: Recent progress and perspectives. *Atmos. Res.* **2019**, *220*, 20–33. [[CrossRef](#)]
142. Schmidl, C.; Bauer, H.; Dattler, A.; Hitzemberger, R.; Weissenboeck, G.; Marr, I.L.; Puxbaum, H. Chemical characterisation of particle emissions from burning leaves. *Atmos. Environ.* **2008**, *42*, 9070–9079. [[CrossRef](#)]

143. Bauer, H.; Schueller, E.; Weinke, G.; Berger, A.; Hitzenberger, R.; Marr, I.L.; Puxbaum, H. Significant contributions of fungal spores to the organic carbon and to the aerosol mass balance of the urban atmospheric aerosol. *Atmos. Environ.* **2008**, *42*, 5542–5549. [[CrossRef](#)]
144. Medeiros, P.M.; Conte, M.H.; Weber, J.C.; Simoneit, B.R.T. Sugars as source indicators of biogenic organic carbon in aerosols collected above the Howland Experimental Forest, Maine. *Atmos. Environ.* **2006**, *40*, 1694–1705. [[CrossRef](#)]
145. Caumo, S.E.S.; Claeys, M.; Maenhaut, W.; Vermeylen, R.; Behrouzi, S.; Safi Shalamzari, M.; Vasconcellos, P.C. Physicochemical characterization of winter PM10 aerosol impacted by sugarcane burning from São Paulo city, Brazil. *Atmos. Environ.* **2016**, *145*, 272–279. [[CrossRef](#)]
146. Medeiros, P.M.; Simoneit, B.R.T. Analysis of sugars in environmental samples by gas chromatography–mass spectrometry. *J. Chromatogr. A* **2007**, *1141*, 271–278. [[CrossRef](#)] [[PubMed](#)]
147. Simoneit, B.R.T.; Elias, V.O.; Kobayashi, M.; Kawamura, K.; Rushdi, A.I.; Medeiros, P.M.; Rogge, W.F.; Didyk, B.M. Sugars Dominant Water-Soluble Organic Compounds in Soils and Characterization as Tracers in Atmospheric Particulate Matter. *Environ. Sci. Technol.* **2004**, *38*, 5939–5949. [[CrossRef](#)] [[PubMed](#)]
148. Khan, J.Z.; Sun, L.; Tian, Y.; Shi, G.; Feng, Y. Chemical characterization and source apportionment of PM1 and PM2.5 in Tianjin, China: Impacts of biomass burning and primary biogenic sources. *J. Environ. Sci.* **2021**, *99*, 196–209. [[CrossRef](#)]
149. Schkolnik, G.; Rudich, Y. Detection and quantification of levoglucosan in atmospheric aerosols: A review. *Anal. Bioanal. Chem.* **2006**, *385*, 26–33. [[CrossRef](#)]
150. Fabbri, D.; Modelli, S.; Torri, C.; Cemin, A.; Ragazzi, M.; Scaramuzza, P. GC-MS determination of levoglucosan in atmospheric particulate matter collected over different filter materials. *J. Environ. Monit.* **2008**, *10*, 1519–1523. [[CrossRef](#)] [[PubMed](#)]
151. Chiara Pietrogrande, M.; Barbaro, E.; Bove, M.C.; Clauser, G.; Colombi, C.; Corbella, L.; Cuccia, E.; Dalla Torre, S.; Decesari, S.; Fermo, P.; et al. Results of an interlaboratory comparison of analytical methods for quantification of anhydrosugars and biosugars in atmospheric aerosol. *Chemosphere* **2017**, *184*, 269–277. [[CrossRef](#)] [[PubMed](#)]
152. Engling, G.; Carrico, C.M.; Kreidenweis, S.M.; Collett, J.L.; Day, D.E.; Malm, W.C.; Lincoln, E.; Min Hao, W.; Iinuma, Y.; Herrmann, H. Determination of levoglucosan in biomass combustion aerosol by high-performance anion-exchange chromatography with pulsed amperometric detection. *Atmos. Environ.* **2006**, *40*, 299–311. [[CrossRef](#)]
153. Iinuma, Y.; Engling, G.; Puxbaum, H.; Herrmann, H. A highly resolved anion-exchange chromatographic method for determination of saccharidic tracers for biomass combustion and primary bio-particles in atmospheric aerosol. *Atmos. Environ.* **2009**, *43*, 1367–1371. [[CrossRef](#)]
154. Saarnio, K.; Teinilä, K.; Aurela, M.; Timonen, H.; Hillamo, R. High-performance anion-exchange chromatography–mass spectrometry method for determination of levoglucosan, mannosan, and galactosan in atmospheric fine particulate matter. *Anal. Bioanal. Chem.* **2010**, *398*, 2253–2264. [[CrossRef](#)] [[PubMed](#)]
155. Simoneit, B.R.T. Biomass burning—A review of organic tracers for smoke from incomplete combustion. *Appl. Geochem.* **2002**, *17*, 129–162. [[CrossRef](#)]
156. Hornig, J.F.; Soderberg, R.H.; Barefoot, A.C.; Galasyn, J.F. Wood smoke analysis: Vaporization losses of PAH from filters and levoglucosan as a distinctive marker for wood smoke. In *Polynuclear Aromatic Hydrocarbons: Mechanisms, Methods, and Metabolism*; Cooke, M., Dennis, A.J., Eds.; Battelle Press: Columbus, OH, USA, 1985; pp. 561–568. ISBN 0935470220.
157. Sullivan, A.P.; Holden, A.S.; Patterson, L.A.; McMeeking, G.R.; Kreidenweis, S.M.; Malm, W.C.; Hao, W.M.; Wold, C.E.; Collett, J.L. A method for smoke marker measurements and its potential application for determining the contribution of biomass burning from wildfires and prescribed fires to ambient PM2.5 organic carbon. *J. Geophys. Res. Atmos.* **2008**, *113*, D22302. [[CrossRef](#)]
158. Chow, J.C.; Watson, J.G.; Kuhns, H.; Etyemezian, V.; Lowenthal, D.H.; Crow, D.; Kohl, S.D.; Engelbrecht, J.P.; Green, M.C. Source profiles for industrial, mobile, and area sources in the Big Bend Regional Aerosol Visibility and Observational study. *Chemosphere* **2004**, *54*, 185–208. [[CrossRef](#)] [[PubMed](#)]
159. Vicente, A.; Alves, C.; Monteiro, C.; Nunes, T.; Mirante, F.; Evtyugina, M.; Cerqueira, M.; Pio, C. Measurement of trace gases and organic compounds in the smoke plume from a wildfire in Penedono (central Portugal). *Atmos. Environ.* **2011**, *45*, 5172–5182. [[CrossRef](#)]
160. Alves, C.; Gonçalves, C.; Fernandes, A.P.; Tarelho, L.; Pio, C. Fireplace and woodstove fine particle emissions from combustion of western Mediterranean wood types. *Atmos. Res.* **2011**, *101*, 692–700. [[CrossRef](#)]
161. Oduber, F.; Calvo, A.I.; Castro, A.; Alves, C.; Blanco-Alegre, C.; Fernández-González, D.; Barata, J.; Calzolari, G.; Nava, S.; Lucarelli, F.; et al. One-year study of airborne sugar compounds: Cross-interpretation with other chemical species and meteorological conditions. *Atmos. Res.* **2021**, *251*, 105417. [[CrossRef](#)]
162. Kuo, L.-J.; Herbert, B.E.; Louchouart, P. Can levoglucosan be used to characterize and quantify char/charcoal black carbon in environmental media? *Org. Geochem.* **2008**, *39*, 1466–1478. [[CrossRef](#)]
163. Hedberg, E.; Johansson, C.; Johansson, L.; Swietlicki, E.; Brorström-Lundén, E. Is levoglucosan a suitable quantitative tracer for wood burning? comparison with receptor modeling on trace elements in Lycksele, Sweden. *J. Air Waste Manag. Assoc.* **2006**, *56*, 1669–1678. [[CrossRef](#)]
164. Khelfa, A.; Finqueneisel, G.; Auber, M.; Weber, J. V Influence of some minerals on the cellulose thermal degradation mechanisms. *J. Therm. Anal. Calorim.* **2008**, *92*, 795–799. [[CrossRef](#)]
165. Dobeles, G.; Rossinskaja, G.; Dizhbite, T.; Telysheva, G.; Meier, D.; Faix, O. Application of catalysts for obtaining 1,6-anhydrosaccharides from cellulose and wood by fast pyrolysis. *J. Anal. Appl. Pyrolysis* **2005**, *74*, 401–405. [[CrossRef](#)]

166. Williams, P.T.; Horne, P.A. The role of metal salts in the pyrolysis of biomass. *Renew. Energy* **1994**, *4*, 1–13. [[CrossRef](#)]
167. Engling, G.; Lee, J.J.; Tsai, Y.W.; Lung, S.C.C.; Chou, C.C.K.; Chan, C.Y. Size-resolved anhydrosugar composition in smoke aerosol from controlled field burning of rice straw. *Aerosol Sci. Technol.* **2009**, *43*, 662–672. [[CrossRef](#)]
168. Schmidl, C.; Luissier, M.; Padouvas, E.; Lasselsberger, L.; Rzaca, M.; Ramirez-Santa Cruz, C.; Handler, M.; Peng, G.; Bauer, H.; Puxbaum, H. Particulate and gaseous emissions from manually and automatically fired small scale combustion systems. *Atmos. Environ.* **2011**, *45*, 7443–7454. [[CrossRef](#)]
169. Alves, C.A.; Vicente, E.D.; Rocha, S.; Vicente, A.M. Organic tracers in aerosols from the residential combustion of pellets and agro-fuels. *Air Qual. Atmos. Heal.* **2017**, *10*, 37–45. [[CrossRef](#)]
170. Fine, P.M.; Cass, G.R.; Simoneit, B.R.T. Chemical characterization of fine particle emissions from fireplace combustion of woods grown in the Northeastern United States. *Environ. Sci. Technol.* **2001**, *35*, 2665–2675. [[CrossRef](#)]
171. Fine, P.M.; Cass, G.R.; Simoneit, B.R.T. Chemical characterization of fine particle emissions from the fireplace combustion of woods grown in the Southern United States. *Environ. Sci. Technol.* **2002**, *36*, 1442–1451. [[CrossRef](#)]
172. Peng, F.; Ren, J.-L.; Xu, F.; Bian, J.; Peng, P.; Sun, R.-C. Comparative Study of Hemicelluloses Obtained by Graded Ethanol Precipitation from Sugarcane Bagasse. *J. Agric. Food Chem.* **2009**, *57*, 6305–6317. [[CrossRef](#)]
173. Vicente, E.D.; Vicente, A.M.; Evtuyugina, M.; Carvalho, R.; Tarelho, L.A.C.; Paniagua, S.; Nunes, T.; Otero, M.; Calvo, L.F.; Alves, C. Emissions from residential pellet combustion of an invasive acacia species. *Renew. Energy* **2019**, *140*, 319–329. [[CrossRef](#)]
174. Sun, J.; Shen, Z.; Zhang, Y.; Zhang, Q.; Wang, F.; Wang, T.; Chang, X.; Lei, Y.; Xu, H.; Cao, J.; et al. Effects of biomass briquetting and carbonization on PM_{2.5} emission from residential burning in Guanzhong Plain, China. *Fuel* **2019**, *244*, 379–387. [[CrossRef](#)]
175. Gosselin, M.I.; Rathnayake, C.M.; Crawford, I.; Pöhlker, C.; Fröhlich-Nowoisky, J.; Schmer, B.; Després, V.R.; Engling, G.; Gallagher, M.; Stone, E.; et al. Fluorescent bioaerosol particle, molecular tracer, and fungal spore concentrations during dry and rainy periods in a semi-arid forest. *Atmos. Chem. Phys.* **2016**, *16*, 15165–15184. [[CrossRef](#)]
176. Verma, S.K.; Kawamura, K.; Chen, J.; Fu, P. Thirteen years of observations on primary sugars and sugar alcohols over remote Chichijima Island in the western North Pacific. *Atmos. Chem. Phys.* **2018**, *18*, 81–101. [[CrossRef](#)]
177. Zhang, Y.-X.; Shao, M.; Zhang, Y.-H.; Zeng, L.-M.; He, L.-Y.; Zhu, B.; Wei, Y.-J.; Zhu, X. Source profiles of particulate organic matters emitted from cereal straw burnings. *J. Environ. Sci.* **2007**, *19*, 167–175. [[CrossRef](#)]
178. Burshtein, N.; Lang-Yona, N.; Rudich, Y. Ergosterol, arabitol and mannitol as tracers for biogenic aerosols in the eastern Mediterranean. *Atmos. Chem. Phys.* **2011**, *11*, 829–839. [[CrossRef](#)]
179. Di Filippo, P.; Pomata, D.; Riccardi, C.; Buiarelli, F.; Perrino, C. Fungal contribution to size-segregated aerosol measured through biomarkers. *Atmos. Environ.* **2013**, *64*, 132–140. [[CrossRef](#)]
180. Elbert, W.; Taylor, P.E.; Andreae, M.O.; Pöschl, U. Contribution of fungi to primary biogenic aerosols in the atmosphere: Wet and dry discharged spores, carbohydrates, and inorganic ions. *Atmos. Chem. Phys.* **2007**, *7*, 4569–4588. [[CrossRef](#)]
181. Kang, M.; Yang, F.; Ren, H.; Zhao, W.; Zhao, Y.; Li, L.; Yan, Y.; Zhang, Y.; Lai, S.; Zhang, Y.; et al. Influence of continental organic aerosols to the marine atmosphere over the East China Sea: Insights from lipids, PAHs and phthalates. *Sci. Total Environ.* **2017**, *607*, 339–350. [[CrossRef](#)]
182. Zhang, Y.; Obrist, D.; Zielinska, B.; Gertler, A. Particulate emissions from different types of biomass burning. *Atmos. Environ.* **2013**, *72*, 27–35. [[CrossRef](#)]
183. Tsai, Y.I.; Sopajaree, K.; Kuo, S.-C.; Yu, S.-P. Potential PM_{2.5} impacts of festival-related burning and other inputs on air quality in an urban area of southern Taiwan. *Sci. Total Environ.* **2015**, *527*, 65–79. [[CrossRef](#)]
184. Chen, J.; Kawamura, K.; Liu, C.Q.; Fu, P. Long-term observations of saccharides in remote marine aerosols from the western North Pacific: A comparison between 1990–1993 and 2006–2009 periods. *Atmos. Environ.* **2013**, *67*, 448–458. [[CrossRef](#)]
185. Theodosi, C.; Panagiotopoulos, C.; Nouara, A.; Zampas, P.; Nicolaou, P.; Violaki, K.; Kanakidou, M.; Sempéré, R.; Mihalopoulos, N. Sugars in atmospheric aerosols over the Eastern Mediterranean. *Prog. Oceanogr.* **2018**, *163*, 70–81. [[CrossRef](#)]
186. Alves, C.A. Characterisation of solvent extractable organic constituents in atmospheric particulate matter: An overview. *An. Acad. Bras. Cienc.* **2008**, *80*, 21–82. [[CrossRef](#)]
187. Rushdi, A.I.; Oros, D.R.; Al-Mutlaq, K.F.; He, D.; Medeiros, P.M.; Simoneit, B.R.T. Lipid, sterol and saccharide sources and dynamics in surface soils during an annual cycle in a temperate climate region. *Appl. Geochem.* **2016**, *66*, 1–13. [[CrossRef](#)]
188. Otto, A.; Simpson, M.J. Analysis of soil organic matter biomarkers by sequential chemical degradation and gas chromatography—Mass spectrometry. *J. Sep. Sci.* **2007**, *30*, 272–282. [[CrossRef](#)]
189. Simpson, C.D.; Dills, R.L.; Katz, B.S.; Kalman, D.A. Determination of levoglucosan in atmospheric fine particulate matter. *J. Air Waste Manag. Assoc.* **2004**, *54*, 689–694. [[CrossRef](#)]
190. Hawthorne, S.B.; Miller, D.J.; Kriege, M.S.; Barkley, R.M. Identification of Methoxylated Phenols as Candidate Tracers for Atmospheric Wood Smoke Pollution. *Environ. Sci. Technol.* **1988**, *22*, 1191–1196. [[CrossRef](#)]
191. Oros, D.R.; Simoneit, B.R.T. Identification and emission factors of molecular tracers in organic aerosols from biomass burning Part 1. Temperate climate conifers. *Appl. Geochem.* **2001**, *16*, 1513–1544. [[CrossRef](#)]
192. Kang, M.; Ren, L.; Ren, H.; Zhao, Y.; Kawamura, K.; Zhang, H.; Wei, L.; Sun, Y.; Wang, Z.; Fu, P. Primary biogenic and anthropogenic sources of organic aerosols in Beijing, China: Insights from saccharides and n-alkanes. *Environ. Pollut.* **2018**, *243*, 1579–1587. [[CrossRef](#)]
193. Kumar, S.; Aggarwal, S.G.; Fu, P.Q.; Kang, M.; Sarangi, B.; Sinha, D.; Kotnala, R.K. Size-segregated sugar composition of transported dust aerosols from Middle-East over Delhi during March 2012. *Atmos. Res.* **2017**, *189*, 24–32. [[CrossRef](#)]

194. Zhang, Z.; Gao, J.; Engling, G.; Tao, J.; Chai, F.; Zhang, L.; Zhang, R.; Sang, X.; Chan, C.Y.; Lin, Z.; et al. Characteristics and applications of size-segregated biomass burning tracers in China's Pearl River Delta region. *Atmos. Environ.* **2015**, *102*, 290–301. [[CrossRef](#)]
195. Barbaro, E.; Feltracco, M.; Cesari, D.; Padoan, S.; Zangrando, R.; Contini, D.; Barbante, C.; Gambaro, A. Characterization of the water soluble fraction in ultrafine, fine, and coarse atmospheric aerosol. *Sci. Total Environ.* **2019**, *658*, 1423–1439. [[CrossRef](#)] [[PubMed](#)]
196. Feltracco, M.; Barbaro, E.; Tedeschi, S.; Spolaor, A.; Turetta, C.; Vecchiato, M.; Morabito, E.; Zangrando, R.; Barbante, C.; Gambaro, A. Interannual variability of sugars in Arctic aerosol: Biomass burning and biogenic inputs. *Sci. Total Environ.* **2020**, *706*, 136089. [[CrossRef](#)] [[PubMed](#)]
197. Horník, Š.; Sýkora, J.; Pokorná, P.; Vodička, P.; Schwarz, J.; Ždímal, V. Detailed NMR analysis of water-soluble organic compounds in size-resolved particulate matter seasonally collected at a suburban site in Prague. *Atmos. Environ.* **2021**, *267*, 118757. [[CrossRef](#)]