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Review

Particulate Matter Emission Factors for Biomass Combustion

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Abstract: Emission factor is a relative measure and can be used to estimate emissions from multiple sources of air pollution. For this reason, data from literature on particulate matter emission factors from different types of biomass were evaluated in this paper. Initially, the main sources of particles were described, as well as relevant concepts associated with particle measurements. In addition, articles about particle emissions were classified and described in relation to the sampling environment (open or closed) and type of burned biomass (agricultural, garden, forest, and dung). Based on this analysis, a set of emission factors was presented and discussed. Important observations were made about the main emission sources of particulate matter. Combustion of compacted biomass resulted in lower particulate emission factors. $PM_{2.5}$ emissions were predominant in the burning of forest biomass. Emission factors were more elevated in laboratory burning, followed by burns in the field, residences and combustors.

Keywords: particulate matter; emission factor; air pollution; biomass burning

1. Introduction

Developed countries are largely dependent on fossil fuels [1]. Renewable energy is now being encouraged as an alternative to fossil fuel [2–4]. Anenberg et al. [5] reported that more than three billion people use solid fuels as the main source of energy in their homes. Saud et al. [6] affirmed that biomass has been extensively used in developing countries such as India.

Charcoal, harvest residues and wood materials are the most common biomass fuels used as energy sources [5]. Not only is the use of in natura biomass fuels becoming more common, compacted biomass, such as briquettes and pellets, is also being used more frequently.

According to Williams et al. [7], one of the most important advantages attributed to the use of renewable fuels such as biomass is its low cost and widespread distribution. Biomass burning, however, is frequently cited as one of the main channels through which particles and pollutant gases enter the atmosphere [8–12].

During biomass burning, particle matter (PM) emissions were dominated by submicrometric particles [9]. Particles can cause severe health effects such us lung cancer, and chronic lung and heart diseases [2,13]. The damage to human health is mainly linked to exposure to PM_{10} and $PM_{2.5}$ [14]. According to Lim et al. [15], the report about Global Disease estimated that in 2010 approximately 3.5 million deaths worldwide in 2010 were attributed to smoke exposure from residential solid fuel combustion.

The effect of particulate matter goes beyond risks to human health. $PM_{2.5}$ and PM_{10} affect weather and reduce visibility, as reported by Pipal and Satsangi [16]. Tiwari et al. [17] described that atmospheric aerosol alters the Earth's radiation balance and causes significant impacts on the weather system. For Tiwari et al. [17], black carbon that is produced through incomplete combustion contributes to global warming because these particles absorb solar light. In the studies of Talukdar et al. [18], it was observed that the concentration of black carbon particles has a positive correlation with environmental heat.

The negative aspects related to biomass combustion emissions may prevent its use as a sustainable fuel. In order to overcome this disadvantage, detailed information is necessary regarding emissions of particulate matter from burning of different types of biomass. This information will help to identify the types of biomass that emit more particles during combustion and may lead to measures for reducing this pollutant.

Few review articles described particle emissions from burning of biomass as fuel [7,10,12,19–26]. Review articles, in general, do not simultaneously address the emission factor (EF) of this pollutant from different emission sources.

The objective of the present review is to present an overview of the main sources through which particle emissions enter the atmosphere. The emissions factors of biomass sampled in an open environment and in a closed environment are considered.

2. Sources of Particulate Matter

Natural detritus and anthropogenic emissions are responsible for the emission of aerosol particles [10,11]. Simoneit [10] mentioned that burning fossil fuels and biomass are the largest sources of particulate matter emissions. Tissari et al. [27] described that wood burning in residences is one of the main contributors to the emission of fine particles during European winter.

Biomass fuel can be defined as any material from vegetal or animal origin which is deliberately burned by humans [28].

There are many sources of biomass combustion, including forest fires, controlled burns, agricultural residues, wood fuel in residences, algae treatment residues, and energy generation [7,11,29]. Simoneit [10] mentioned other sources of particle emission from biomass burning, such as dung burning and domestic waste burning. Fast growing wood, forest and agriculture residues, and the sub-products of municipal and industrial processes are the main sources of biomass.

The properties and uses of different types of biomass vary significantly, as well as their advantages and disadvantages [2]. Garbaras et al. [9] report that these properties can significantly affect the air quality during combustion processes. Biomass can be employed either in compacted form or in its natural state. Singh [3] described that the biomass can be compacted by mechanical processes (for example, bales, pellets, cubes, and briquettes) and by pyrolysis (for example, torrefaction, slow pyrolysis, and fast pyrolysis).

3. Particulate Matter Measurements

Nussbaumer et al. [12] and Wilson et al. [19] emphasized the importance of measuring particle emission concentrations and amounts. They stated that the impact of particles on human health and the environment can be determined by their PM parameters. With the knowledge of such parameters, emission standards can also be developed and implemented.

Among the measuring parameters, Nussbaumer et al. [12] mentioned the measurement of the particle shape and its morphology. The characteristics of particle emission are usually related to physical and chemical parameters. The most reported of them being mass concentration, diameter distribution, concentration in number and size distribution in number [24].

Another particulate measurement is the emission factor. The emission factor quantifies the magnitude of emissions [11]. The EF has been used in a number of different studies to quantity aerosol emissions [30–34].

An emission factor is a representative value that relates the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. EFs are usually expressed as the mass of the pollutant divided by unit mass, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per mega gram of coal burned). These factors make it possible to estimate emissions from various sources of air pollution. In most cases, they are simply averages of all available data of acceptable quality. They are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average). Emissions factors have long been fundamental in developing national, regional, state, and local emissions inventories for air quality management decisions and in developing emission control strategies [35]. For example, in biomass combustion the EF relates the mass of pollutant emitted into the atmosphere to fuel consumption. This measure allows comparison between emissions from different biomass sources. Janhäll et al. [22] and Tissari et al. [36] described that the emission factor can be discussed in terms of particle mass (EF_{PM}) or particle number (EF_{PN}).

If the particle concentration and the volume of air sampled over time are determined, the emission factor in mass can be calculated. The emission factor of PM, considering the particle concentration, can be calculated using Equation (1) [37].

$$EF_{PM} = \frac{C \cdot V_{Total}}{m_{fuel\ (dry\ basis)}} = \left(\frac{g_{PM}}{kg_{fuel}}\right) \quad (1)$$

where C is the average concentration of PM (mg/m^3), V_{Total} is the total volume of the gas sampled during the experiment (m^3), and $m_{fuel\ (dry\ basis)}$ is the mass of dry fuel consumed (kg).

The emission factor in mass quantifies the emission of a pollutant in terms of amount of dry fuel that is actually burned (g/kg) [22,38–40] or as a function of energy produced in a burned (mg/MJ) [12]. EFs can be given in energy units (mg/MJ) using the low heating values (LHVs) of the burned fuels for units conversion [41].

Studies have evaluated the emission factors of particles from some groups of specific plants, that include softwoods, hardwoods and grasses [1,10,30,42–44].

4. Studies of Particulate Matter Sampling

Most studies of sampling of atmospheric pollutants from biomass combustion involve two main types of sampling: open and closed environment.

Field measurements in an open environment yield very reliable results, even though they are more labor intensive, expensive, and time consuming, as discussed by Shen et al. [45]. According to the authors, simulation studies in the closed environment of a laboratory have the advantage of being able to study different pollutants in different burning conditions in a relatively timely manner. Fuel properties can also be studied in laboratory, as well as the effects of different burning conditions on pollutant emissions. Simoneit [10] commented that pollutants can also be measured by sampling using airplanes or by remote sensing.

In Table 1, sampling done in field burns, remote sensing sampling and sampling using airplanes were considered as examples of open environment sampling. Samples taken from combustors and in the laboratory were classified as sampling in a closed environment. Biomass burning in residential burners was classified as open burning; the sampling was carried out directly in the atmosphere. Sampling in residential burners was classified as a closed environment when performed in confined ducts.

Table 2 presents a summary of results for particulate matter sampling in different burning environments.

Table 1 presents the classification of PM emission factors considering the sampling environment and the biomass type.

Table 1. Classification of PM emission factors by sampling environment and biomass type.

	Sampling	Biomass
Sampling in open places	Field	Forest Agriculture and garden waste
	Remote sensing	Multiple types of biomass
	Aircraft	Multiple types of biomass
Sampling in close places	Combustors	Compacted biomass In natura biomass
	Residences	Compacted biomass In natura biomass
	Laboratory	Compacted biomass In natura biomass

Table 2. Summary of results in the literature for particulate matter sampling in different burning environments.

Fuel	Field	Remote Sensing	Aircraft	Combustors	Residences	Laboratory	Total
Forest biomass (in nature)	10	0	0	3	13	8	34
Agricultural and garden waste (in nature)	8	1	0	0	5	10	24
Forest biomass (compacted)	0	0	0	0	8	1	9
Agricultural and garden waste (compacted)	0	0	0	2	1	1	4
Different types of biomass	0	3	3	0	0	0	6
Dust	0	0	0	0	1	4	5
	18	**4**	**3**	**5**	**28**	**24**	**82**

The largest number of studies was carried out with forest biomass (in natura) and agricultural and garden waste (in natura) (71%). However, only 16% of the studies were of these types of biomass in the compacted form. Compacted biomass tends to emit different levels of pollutants in relation to in natura biomass [31,36,41,46]. According to Ghafghazi et al. [23], biomass pellets are high quality fuel. Fuel in the form of pellets generates less particle matter emissions than other types of wooden fuels. Ghafghazi et al. [23] reported that emissions of particulate matter can be well below the emissions limit, when wood pellets are burned in grid burners equipped with electrostatic precipitators. According to Shen et al. [41], biomass pellets can be a clean substitute for biomass in its traditional form. These facts justify further study of emissions from compacted biomass combustion.

When compared to studies found in the literature, regarding the burning environment, three main locations were: residential (34%), laboratory (29%), and field burns (22%). There are more studies on residential burners and laboratory burning simulations because these two are less complex, less expensive, and emissions can be collected more easily than in burning conducted in the field. In addition, variables that could influence the combustion process can be controlled in laboratory burning experiments [47].

4.1. Open Environment Sampling

In open burning, the combustion products are emitted directly into the atmosphere without passing through a chimney or a duct. Many activities can be regarded as open burnings, such as combustion of agriculture residues, of wood in stoves, and industrial and domestic residues.

Unintentional fires, such as forest fires and accidental fires caused by recreational activities with fireworks and barbecues also were considered open burnings [21].

Burning biomass in agricultural areas, forest fires and residential burning significantly contribute to loads of atmospheric aerosols [44]. Forest, grass and turf combustion produces nearly two pentagrams/year of carbon, which affects the climate and air quality [48].

Tropical forests are acknowledged as an important aerosol source from combustion of biomass [49].

4.1.1. Field

(a) Prescribed Forest Burning and Forest Fires

Emissions from forest burning are associated to prescribed forest burning or forest fires.

Prescribed burning became a strategy to reduce the risk of fires. This technique is based on controlled fuel combustion [42]. Intentional prescribed burnings are regulated by the Clean Air Act in the United States [29].

Intentional burns are planned using predicted conditions to reach derived objectives for management of vegetation. These include removal of accumulated fuel in the area, wildlife habitat improvement and forest regeneration. In order to use controlled fire, managers must provide estimative of combustion products.

Different to what happens in prescribed burnings, there is no fire control in forest fires. Forest fires can be started by humans (intentional or negligent) or have natural causes (solar rays, electrical discharges, etc.).

Considerable attention has been given to environmental effects of forest fires [21]. They affect the ecosystem and the biodiversity, and produce greenhouse gases.

Table 3 shows values for emission factor found in the literature for field burning of forest biomass (in natura).

Table 3. EF values found in the literature for field burning of forest biomass (in natura).

Reference	Fuel	Size	EF PM (g/kg)		
[50]	Primary Forest	$PM_{2.5}$	14.80	±	_
[50]	Pasture	$PM_{2.5}$	18.70	±	_
Average:			**16.75**	±	**2.76**
[39]	Shrubland	$PM_{2.8}$	**3.40**	±	_
[51]	Amazon biomass—flaming	TSP	7.45	±	_
[51]	Amazon biomass—intermediate	TSP	4.21	±	_
[51]	Amazon biomass—smoldering	TSP	3.85	±	_
[51]	Amazon biomass—average	TSP	4.84	±	_
Average:			**5.09**	±	**1.63**

Average $PM_{2.5}$ emission factor from in natura burning of forest biomass in the field was 16.75 ± 2.76 g/kg. This value was higher to Total Suspended Particulates (TSP) emission factor (5.09 ± 1.63 g/kg), found in the literature during field burning of forest biomass in natura. Wardoyo et al. [11] reported that burning in field conditions mainly occurs in the flame and smoldering phases. Particles are produced during these two phases, but they can vary in size depending on the phase. Some authors observed that fine particles are mainly emitted in the flame phase, during which Modified Combustion Efficiency (MCE) is higher [30,52,53]. Tissari et al. [27] verified that, in smoldering, the emission factor of PM_1 and PM_{10} were about six times higher than in normal combustion.

Alves et al. [39] studied prescribed burns in a forest dominated by shrub and some pine trees in Lousã Mountain, Portugal. The authors sampled $PM_{2.5}$ and $PM_{2.5–10}$, and evaluated water soluble ions,

level of organic carbon (OC) and elemental carbon (EC), as well as metals. These authors obtained a $PM_{2.5}$ EF of 3.4 g/kg.

Some authors have studied emission factors for $PM_{2.5}$ in the Amazon forest, Brazil [51,54]. In the studies by Neto et al. [51], biomass consumption, as well as emission factors for CO_2, CO, and hydrocarbons were also evaluated. Total biomass consumption was 23.9%. Average emission factor for $PM_{2.5}$ was 4.8 g/kg.

Zhang et al. [42] evaluated the $PM_{2.5}$ emission markers in several different types of controlled burns. Emissions were characterized through prescribed burns in the Western of the United States. Holden et al. [55], as well as Zhang et al. [42], also evaluated emissions from burns in the Western of the United States. The authors determined the contributions from biomass burning to the $PM_{2.5}$ emissions.

$PM_{2.5}$ mass and chemical species concentrations were determined in the experiments of Tao et al. [56].The objective of their study was to identify potential sources of $PM_{2.5}$ emissions. Samples were collected in Chengdu, in China, during 2009 and 2010. The annual average concentration of $PM_{2.5}$ was 165.1 $\pm$ 85.1 mg/m^3.

Elsasser et al. [43] investigated the main markers present in PM_1 and $PM_{2.5}$ in emissions from wood combustion in the Augsburg, Germany (2010-Winter). Krecl et al. [4] analyzed elemental and organic carbon for PM_{10} from wood combustion during the winter, in a residential area north of Sweden. The authors also measured the content of light-absorbing carbon.

(b) Burning of Agricultural and Garden Residues

Burning agriculture residues is an inexpensive way to rotate crops and control insects and diseases, in addition to avoiding the appearance of invading weeds [21]. Health and environmental hazards caused by the burning of agriculture residues must be acknowledged, even though this activity is thought to be economical and practical [21,57].

Experimental data from simulated open burns and in situ burns of different types of agricultural products, such as rice, wheat, sugar cane and other crops had a variety of emissions, such as soot and particles, carbon monoxide, methane, and volatile organic compounds [21].

As stated by Hossain et al. [44], rice straw is one of the main materials burned in agricultural fields of Korea and throughout Asia. Ryu et al. [49] also mentioned that in Korea open field burns of agricultural residues, after harvest is a common practice in order to promote agriculture productivity. There are two typical periods of seasonal burns in Korea. Agricultural residues are burned after barley harvest in the spring and after rice harvest in the fall.

In Brazil, sugarcane is another agricultural culture that has been submitted to burning. For Brazil, sugar cane has become economically important; approximately 50% of it is used to produce ethanol [37]. During pre-harvest the common practice is to burn the cane straw to clean the field, which releases a series of pollutants to the atmosphere.

Table 4 shows values for emission factor found in the literature for field burning of agricultural and garden biomass in natura. Average EFs from field burning of agricultural and garden biomass in natura were 6.85 $\pm$ 0.14 g/kg for $PM_{2.5}$ and 9.40 $\pm$ 3.50 g/kg for PM_{10}.

Table 4. EF values found in the literature for field burning of agricultural and garden biomass (in natura).

Reference	Fuel	Size	EF PM (g/kg)		
[57]	Rice straw	$PM_{2.5}$	8.30	$\pm$	2.70
[58]	Crop residue	$PM_{2.5}$	5.40	$\pm$	2.90
Average:			**6.85**	$\pm$	**0.14**
[57]	Rice straw	PM_{10}	**9.40**	$\pm$	**3.50**

During a burning period of barley agricultural residues in Korea rural areas, Ryu et al. [49] sampled PM_{10} and $PM_{2.5}$. The authors investigated particle concentration and chemical characteristics. Average mass concentrations for fine particles were 67.9 mg/m^3 and for coarse particles, it was 18.7 mg/m^3. The highest $PM_{2.5}$ concentration was 110.3 mg/m^3, which occurred during the period of biomass burning.

Oanh et al. [57] burned rice straw in Thailand. The authors analyzed emission factors for $PM_{2.5}$ and $PM_{2.5–10}$, and PM chemical components. $PM_{2.5}$ average emission factor was 8.3 ± 2.7 g/kg. PM_{10} resulting EF (9.4 ± 3.5 g/kg) was not significantly higher than $PM_{2.5}$. In the studies by Hossain et al. [44], as with the studies by Oanh et al. [57], emissions for burning rice straw were evaluated.

Prado et al. [59] evaluated respiratory problems in workers exposed to $PM_{2.5}$ from burning sugarcane in Brazil. The evaluation was during the sugarcane non-harvest and harvest periods. The study was based on questionnaires about respiratory symptoms and environmental measures for $PM_{2.5}$ concentration. A spectrophotometer was used to determine the particle concentration. Results showed that $PM_{2.5}$ concentration rose from 8 mg/m^3 in the non-harvest period to 61 mg/m^3 in the harvest period. Prado et al. [59] concluded that non-mechanized sugarcane harvest with prior field burns affects workers and inhabitants of neighboring cities, exposing them to high levels of pollutants.

4.1.2. Remote Sensing

Among the studies referring to air pollution that involve remote sensing, some can be mentioned [48,60–62]. França et al. [60] used remote sensing emission maps to estimate annual emissions from pre-harvest burning of sugarcane straw, in the state of São Paulo, Brazil. The emission factor was determined through the image analysis of the fire focus. The main image source was the Thematic Mapper sensor onboard the Landsat-5 satellite. Other images were employed, such as those obtained with the Charge-Coupled Device sensor (CCD), onboard the China-Brazil Resources Satellite Terra. Fire counts within the sugarcane areas were provided by Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS). Average $PM_{2.5}$ emissions in the period from 2006 to 2008 were 45 ± 6 g/kg.

The emissions of aerosol from biomass burning in different regions in South America were determined by Videla et al. [62]. The authors based their research on data sets from satellites, such as the observations made by the MODIS sensor onboard the NASA-Terra spacecraft.

Annual global mortality due to landscape burning was estimated in the studies by Johnston et al. [48]. Combined results from a chemical transport model, GEOS-Chem, and satellite observation results were used to determine $PM_{2.5}$ emissions. Satellite observations referred to the optical depth of aerosol (AOD). The AOD was analyzed by using the MODIS sensors and Multi-angle Imaging Spectroradiometer (MISR), of the NASA-Terra satellite. The mortality average attributed to smoke exposure from landscape burning was 339 thousand deaths per year. The authors concluded that emissions from burning are an important contributor to global mortality. Johnston et al. [48] pointed out the extinction of practices to burn tropical forests as a solution to substantially reduce adverse health results found in their work.

Evans et al. [61] also evaluated mortality associated with long-term exposure to fine particles. Global levels of exposure to $PM_{2.5}$ were obtained from MODIS and MISR satellites. The global fraction of adult mortality attributable to $PM_{2.5}$ was 8.0% (5.3%–10.5%) for cardiopulmonary disease, 12.8% (5.9%–18.5%) for lung cancer, and 9.4% (6.6%–11.8%) for heart ischemic disease. The authors concluded their study by emphasizing the viability of using satellites to evaluate air pollution impacts on the health of the population on a global scale. According to Evans et al. [61], satellites can be used to calculate global estimates of mortality attributable to $PM_{2.5}$, which are higher than those based on measurements taken in a fixed place at ground level.

4.1.3. Aircraft

Different types of biomass burned in the field and sampled by aircraft were studied [11,52,53]. EFs found for this type of burning are summarized on Table 5. Average EF for particles with diameter smaller than 2.8 µm was 7.47 ± 2.35 g/kg.

Table 5. EF values found in the literature for burning of different types of biomass with aircraft sampling.

Reference	Fuel	Size	EF PM (g/kg)		
[53]	Amazon biomass—free troposphere	$PM_{2.8}$	8.60	±	_
[53]	Amazon biomass—boundary layer	$PM_{2.8}$	4.50	±	_
[53]	Amazon biomass—residual smoldering combustion	$PM_{2.8}$	9.20	±	_
[52]	Tropical forest	$PM_{2.5}$	4.50	±	1.64
[52]	Crop residue and tropical forest	$PM_{2.6}$	7.82	±	1.83
[52]	Savanna	$PM_{2.7}$	7.65	±	2.54
[52]	Pine-Oak forests	$PM_{2.8}$	11.33	±	4.13
[52]	Crop residue	$PM_{2.5}$	6.19	±	2.36
Average:			**7.47**	**±**	**2.35**

Yokelson et al. [52] reported emission factors for gases and $PM_{2.5}$ in the South of Mexico in March 2006. These measurements were done for six fires from harvesting residues, three fires in dry tropical forests, eight burns of savanna, one garbage burn, and seven Pine-Oak forest fires. The authors observed that the number of particles in this size range was 15% for MCE of 0.88, increasing to 60% for MCE of 0.98.

In Amazon fires, Guyon et al. [53] used an equipped aircraft to analyze $PM_{2.5}$ and gas compounds. The authors observed that the number of particles generated by biomass combustion depends on fire conditions (combustion efficiency). The emission factor measured in the free troposphere was 8.6 g/kg and in the boundary layer was 4.5 g/kg. Considering the correction for residual smoldering combustion, which is not sampled by aircrafts, the emission factor in the boundary layer was 9.2 g/kg.

Wardoyo et al. [11] also obtained particle size distribution using aircraft. Their data were collected in fires during the dry season in Australia (June and September 2003).

4.2. Closed Environment Sampling

Sampling of particulate matter in closed environments involved the burning of solid biomass in combustors, residences and the laboratory.

4.2.1. Combustors

Biomass is primarily burned to generate energy. According to Estrellan and Iino [21], wood combustion is a popular source of energy, mainly because of the need to reduce greenhouse gas emissions by fossil fuels.

The use of wood and other types of biomass as industrial fuel can be done with in natura biomass or compacted biomass in the form of pellets and briquettes.

Even though wood produces less emissions when compared to fossil fuels, it is still a large source of organic carbon emissions [21].

(a) Compacted Biomass

Tables 6 and 7 show emission factor found in the literature for compacted forest biomass and compacted agricultural and garden biomass in combustors.

Table 6. EF values found in the literature for burning of compacted forest biomass in combustors.

Reference	Fuel	Size	EF PM (g/kg)		
[36]	Wood—nominal load	PM_1	0.28	±	0.04
[36]	Wood—partial load	PM_1	0.43	±	0.04
[36]	Wood and kaolin—nominal load	PM_1	0.38	±	0.01
Average:			**0.36**	**±**	**0.08**
[63]	Wood pellets—low load	$PM_{2.5}$	0.23	±	0.08
[63]	Wood pellets—high load	$PM_{2.5}$	0.25	±	0.05
Average:			**0.24**	**±**	**0.02**
[36]	Wood—nominal load	PM_{10}	0.21	±	_
[36]	Wood—partial load	PM_{10}	0.40	±	_
[36]	Wood and kaolin—nominal load	PM_{10}	0.37	±	_
Average:			**0.33**	**±**	**0.10**

Table 7. EF values found in the literature for burning compacted agriculture and garden biomass in combustors.

Reference	Fuel	Size	EF PM (g/kg)		
[36]	Oat and kaolin—nominal load	PM_1	0.29	±	_
[36]	Oat—nominal load	PM_1	0.49	±	0.04
[36]	Oat—partial load	PM_1	0.65	±	0.06
[36]	Oat and peat—nominal load	PM_1	0.97	±	0.11
[36]	Oat and peat—partial load	PM_1	0.70	±	0.01
[36]	Rape seed—nominal load	PM_1	0.32	±	0.07
[36]	Rape seed bark—nominal load	PM_1	0.48	±	0.02
Average:			**0.56**	**±**	**0.24**
[63]	Grass pellets A—low load	$PM_{2.5}$	0.54	±	0.06
[63]	Grass pellets B—low load	$PM_{2.5}$	0.79	±	0.08
[63]	Grass pellets C—low load	$PM_{2.5}$	0.53	±	0.03
[63]	Grass pellets D—low load	$PM_{2.5}$	0.40	±	0.12
[63]	Grass pellets E—low load	$PM_{2.5}$	0.41	±	0.08
[63]	Grass pellets A—high load	$PM_{2.5}$	0.76	±	0.05
[63]	Grass pellets B—high load	$PM_{2.5}$	0.92	±	0.06
[63]	Grass pellets C—high load	$PM_{2.5}$	0.61	±	0.06
[63]	Grass pellets D—high load	$PM_{2.5}$	0.57	±	0.06
[63]	Grass pellets E—high load	$PM_{2.5}$	0.54	±	0.06
Average:			**0.61**	**±**	**0.17**
[36]	Oat and kaolin—nominal load	PM_{10}	0.72	±	_
[36]	Oat—nominal load	PM_{10}	0.40	±	_
[36]	Oat—partial load	PM_{10}	0.67	±	_
[36]	Oat and peat—nominal load	PM_{10}	0.85	±	_
[36]	Oat and peat—partial load	PM_{10}	0.72	±	_
[36]	Rape seed—nominal load	PM_{10}	0.27	±	_
Average:			**0.61**	**±**	**0.22**

Average EFs for burning compacted forest biomass in combustors were 0.36 ± 0.08 g/kg, 0.24 ± 0.002 g/kg, and 0.33 ± 0.10 g/kg, respectively for PM_1, $PM_{2.5}$ and PM_{10}.

Burning compacted agricultural and garden biomass in combustors resulted in average emissions factors of 0.56 ± 0.24 g/kg, 0.61 ± 0.17 g/kg, and 0.61 ± 0.22 g/kg, respectively for PM_1, $PM_{2.5}$ and TSP, as seen on Table 7.

Chandrasekaran et al. [63] burned five different types of grass and wood pellets in a boiler with an output capacity of 113,900 BTU/h. Emissions were evaluated for high and low load conditions.

These authors monitored emissions of PM_{10}, $PM_{2.5}$, NO_x, SO_2 and CO, and studied how the properties of fuel affected the emissions. Gas flow samples were collected after a dilution tunnel. PM_{10} emissions from combustion of grass pellets were higher than the emissions from wood pellets.

The influence of different types of biomass on emission of PM_1 and gases was evaluated by Tissari et al. [36]. Oat seeds, rape seeds, rape bark pellets, and wood pellets were the main fuels. Burning was carried out in a pellet burner (20 kW) and gas flow was diluted before sampling. PM_1 emissions from the cereal-based fuels did not significantly differ from emissions of wood fuels.

(b) Biomass in Natura

Physical and chemical particle properties (PM_1) generated by wood chip combustion were analyzed by Torvela et al. [64]. The fuel was burned in a biomass combustor with a nominal power of 40 kW. Before sampling, escape gas was diluted using porous diluting tubes and diluting ejectors in series.

Leskinen et al. [65], as well as Torvela et al. [64] evaluated the physical and chemical properties of PM_1, and gas emissions. Leskinen et al. [65] evaluated combustion of wood chips in different burning conditions (efficient, intermediate and smoldering). Gas flow was diluted before PM_1 sampling in order to reduce particle concentration to a measurable level and produce enough sample flow rate in the measuring instruments. The authors measured concentrations of particles in number, distributions of size in number and aerodynamic size.

4.2.2. Residences

(a) Compacted Biomass

Tables 8 and 9 present EF values found in the literature for residential burning of compacted forest biomass and residential burning of compacted agricultural and garden biomass, respectively.

Table 8. EF values found in the literature for residential burning of compacted forest biomass.

Reference	Fuel	Size	EF PM (g/kg)		
[66]	Briquettes—fireplace	$PM_{2.5}$	15.30	±	_
[66]	Briquettes—woodstove	$PM_{2.5}$	4.20	±	_
[1]	Briquettes and pellets—woodstove	$PM_{2.5}$	7.10	±	4.80
[1]	Briquettes and pellets—fireplace	$PM_{2.5}$	12.00	±	1.70
[31]	Charcoal briquette	$PM_{2.5}$	0.20	±	0.10
Average:			**7.76**	**±**	**6.02**
[41]	Pine wood pellet—mode I	PM_{10}	0.49	±	0.13
[41]	Pine wood pellet—mode II	PM_{10}	1.85	±	0.79
Average:			**1.17**	**±**	**0.96**
[32]	Wood pellets—stove	TSP	1.91	±	_
[32]	Wood pellets—boiler	TSP	1.07	±	_
Average:			**1.49**	**±**	**0.60**

Table 9. EF values found in the literature for residential burning of compacted agriculture and garden biomass.

Reference	Fuel	Size	EF PM (g/kg)		
[46]	Biofuel briquette—improve stove	TSP	3.20	±	0.90
[46]	Biofuel briquette—traditional stove	TSP	4.80	±	1.40
[41]	Corn straw pellet—mode I	TSP	2.41	±	1.32
[41]	Corn straw pellet—mode II	TSP	2.85	±	1.18
Average:			**3.32**	**±**	**0.22**

For residential burning of compacted forest biomass, $PM_{2.5}$ had the highest average EF, 7.76 ± 6.02 g/kg, followed by 1.49 ± 0.60 g/kg for TSP, and 1.17 ± 0.96 g/kg for PM_{10}.

Average emission factor for TSP in residential burning of compacted agricultural and garden biomass was 3.32 ± 0.22 g/kg.

PM EF was lower for pellet burning than for non-compacted fuel burning [41]. Another study reported that PM emission factor was significantly higher in briquette combustion than with fuel wood (raw) [46]. However, the authors have reported that the briquettes were produced with pine powder and cow dung binder, which lead to higher emissions and justify this result.

PM EF have been studied in different residential burners, including fireplaces [1,32,66,67], pellet stoves [32,68] and woodstoves [1,32,41,46,66–68]. Emission factors for fine particles from burning in woodstoves seem to be inferior to those in the fireplace [32,67], but higher than an automatic pellets appliance stove [32].

Emissions from burning native wood, in European countries, were investigated in the studies by Kistler et al. [68]. Burning took place in a manual feed woodstove (8 kW) and in a pellet stove (9 kW). The fuel studied included wood from deciduous and coniferous species; briquettes from deciduous wood species; pellets from coniferous species; and garden biomass. Particle matter (PM_{10}) was collected in quartz fiber filters, pre and after dilution of escape gases, during all of the combustion time. Results were discussed regarding emission rate in mg/MJ. Emission factors ranged from 16 to 32 mg/MJ for compacted wood.

Four manually fed wood burners (open fireplace, closed fireplace, traditional stove and advanced stove) and two automatic pellets burners (pellet stove and pellet boiler) were used in the experiments by Ozgen et al. [32]. In these experiments, emission factors were determined for gases and particulate matter emitted by burning of European fuels. Five types of wood were used to feed manual devices and two pellet types (low and high quality) were employed for tests done in the boiler and automatic stove. Total PM emissions were measured after dilution of combustion gases, using 47 mm diameter filters. The authors did not observe higher difference between the different types of wood.

Seven tree species grown in Portugal and briquettes from forest residues were burned in the experiments by Alves et al. [66]. Burning took place in a fireplace and woodstove to determine $PM_{2.5}$ emission factor and aerosol chemical composition. Gonçalves et al. [67] also evaluated emissions in Portuguese biomass. The authors determined emission factors, carbon contents and quantified organic compounds from fine particles. The experiments had the objective of evaluating the effects of different burning devices (woodstove vs. fireplace), and burning temperature on emissions (cold and hot ignition). The wood was burned in natura and compacted in the form of briquettes. Collection of $PM_{2.5}$ was carried out in a dilution tunnel. Emission factors for $PM_{2.5}$ in woodstove were in the range of 5.62–25.8 g/kg for cold ignition and 1.66–16.0 g/kg for in hot ignition. EFs for fireplace were between 8.11 and 29.0 g/kg, in cold ignition, and between 0.84 and 21.7 g/kg, in hot ignition. The authors concluded that emissions of $PM_{2.5}$ were higher in the cold ignition experiments. In order to create a national emission inventory from wood combustion in fireplaces and woodstoves, Gonçalves et al. [1] gathered data from a series of burning tests carried out with seven species of Portuguese wood. The inventory included $PM_{2.5}$, organic and elementary carbon, and other compounds. Estimated $PM_{2.5}$ emissions in Portugal were 10.96 kt/year for wood combustion. This value represented 30% of the global estimate of 36.30 kt/year.

Shen et al. [41] burned pellets of pine wood and corn straw in a pellet burner. The authors also burned raw pine wood and raw corn straw in a traditional stove. The authors determined EF for CO, organic carbon, elementary carbon, PM, and PAH. Combustion gases were diluted and then sampled in triplicate. Average PM EF collected in 25 mm diameter filters was 71.0 ± 54.0 mg/MJ, for pine wood pellets, and 188 ± 87 mg/MJ, for corn straw pellets.

Njenga et al. [31] evaluated the potential use of briquettes obtained from recycled vegetal coal powder, as residential fuel in Kenya. The objective of the study was to quantify benefits from using this type of briquette on the reduction of Greenhouse Gases (GHG) emissions. Emissions of GHG

were quantified by using the Life Cycle Assessment methodology. Emission factors of $PM_{2.5}$ were determined from biomass burning in stoves that use charcoal briquettes, charcoal and kerosene. The authors concluded that the briquette produced from charcoal powder has potential to reduce Greenhouse Gases, since it produces low emissions [31].

Emission factors for carbon monoxide and aerosols, from burning of wood, dung cake and biofuel briquettes, were reported in the studies by Venkataraman and Rao [46]. The different types of biomass were burned in traditional stoves and improved stoves used in India.

(b) Biomass in Natura

In residential burning of forest biomass in natura (Table 10), the emission factor was higher for $PM_{2.5}$ (10.50 ± 5.47 g/kg), as occurred at field experiments of this material. The average emission factors were 3.95 ± 4.02, 1.85 ± 0.22 and 0.38 ± 0.23 g/kg, respectively for TSP, PM_{10} and PM_1.

Table 10. EF values found in the literature for residential burning of forest biomass in natura.

Reference	Fuel	Size	EF PM (g/kg)		
[27]	Birch wood—normal combustion	PM_1	0.54	±	_
[27]	Birch wood—smoldering combustion	PM_1	0.22	±	_
Average:			**0.38**	**±**	**0.23**
[66]	Maritime pine	$PM_{2.5}$	14.20	±	_
[66]	*Eucalyptus*—fireplace	$PM_{2.5}$	20.20	±	_
[66]	Cork oak—fireplace	$PM_{2.5}$	13.40	±	_
[66]	Golden wattle—fireplace	$PM_{2.5}$	10.00	±	_
[66]	Olive—fireplace	$PM_{2.5}$	9.90	±	_
[66]	Portuguese oak—fireplace	$PM_{2.5}$	19.10	±	_
[66]	Holm oak—fireplace	$PM_{2.5}$	16.00	±	_
[66]	Maritime pine—woodstove	$PM_{2.5}$	16.30	±	_
[66]	*Eucalyptus*—woodstove	$PM_{2.5}$	6.70	±	_
[66]	Cork oak—woodstove	$PM_{2.5}$	15.10	±	_
[66]	Golden wattle—woodstove	$PM_{2.5}$	11.70	±	_
[66]	Olive—woodstove	$PM_{2.5}$	6.20	±	_
[66]	Portuguese oak—woodstove	$PM_{2.5}$	9.80	±	_
[66]	Holm oak—woodstove	$PM_{2.5}$	10.20	±	_
[1]	Maritime pine—woodstove	$PM_{2.5}$	5.20	±	4.30
[1]	Golden wattle—woodstove	$PM_{2.5}$	7.90	±	4.30
[1]	Holm oak—woodstove	$PM_{2.5}$	5.80	±	3.90
[1]	Eucalyptus—woodstove	$PM_{2.5}$	10.00	±	6.70
[1]	Cork oak—woodstove	$PM_{2.5}$	8.30	±	6.10
[1]	Olive—woodstove	$PM_{2.5}$	8.70	±	4.50
[1]	Portuguese oak—woodstove	$PM_{2.5}$	13.00	±	8.30
[1]	Maritime pine—fireplace	$PM_{2.5}$	6.90	±	3.60
[1]	Golden wattle—fireplace	$PM_{2.5}$	7.80	±	6.20
[1]	Holm oak—fireplace	$PM_{2.5}$	13.00	±	8.30
[1]	Eucalyptus—fireplace	$PM_{2.5}$	12.00	±	7.60
[1]	Cork oak—fireplace	$PM_{2.5}$	21.00	±	10.00
[1]	Olive—fireplace	$PM_{2.5}$	18.00	±	10.00
[1]	Portuguese oak—fireplace	$PM_{2.5}$	14.00	±	9.70
[31]	Charcoal	$PM_{2.8}$	0.90	±	0.70
[31]	Charcoal briquette	$PM_{2.8}$	0.20	±	0.10
[58]	Fuel wood log	$PM_{2.8}$	1.80	±	1.30
[58]	Brushwood/branch	$PM_{2.8}$	2.60	±	0.65
Average:			**10.50**	**±**	**5.47**
[69]	Red oak an Eastern Hem-lock	PM > 4	4.00	±	_
[41]	Raw pine wood	PM_{10}	1.59	±	0.32
[45]	Populus tomentosa Carr. and Paulownia tomentosa	PM_{10}	2.10	±	0.63

Table 10. *Cont.*

Reference	Fuel	Size	EF PM (g/kg)		
Average:			**1.85**	±	**0.22**
[70]	Eastern white pine and Red oak	TSP	12.81	±	_
[46]	Wood—improve metal stove	TSP	1.20	±	0.80
[46]	Wood—improve fired-clay stove	TSP	1.10	±	0.20
[46]	Wood—traditional mud stove	TSP	2.80	±	0.50
[46]	Wood—improve fired-clay stove	TSP	0.90	±	0.30
[32]	Wood—open fireplace	TSP	8.42	±	_
[32]	Wood—closed fireplace	TSP	3.01	±	_
[32]	Wood—traditional stove	TSP	2.93	±	_
[32]	Wood—advanced stove	TSP	2.35	±	_
Average:			**3.95**	±	**4.02**

Table 11 shows the EF of residential burning of agricultural and garden biomass in natura. The average emission factors were 4.24 ± 0.57 g/kg and 8.03 ± 3.57 g/kg, for PM_{10} and TSP, respectively.

Table 11. EF values found in the literature for residential burning of agricultural and garden biomass in natura.

Reference	Fuel	Size	EF PM (g/kg)		
[41]	Raw corn straw	PM_{10}	4.65	±	0.06
[71]	Corn straw	PM_{10}	3.84	±	1.02
Average:			**4.24**	±	**0.57**
[72]	Wheat straw—1 year stove	TSP	9.80	±	4.70
[72]	Rape straw—1 year stove	TSP	3.70	±	3.00
[72]	Rice straw—1 year stove	TSP	5.20	±	2.90
[72]	Cotton straw—1 year stove	TSP	5.70	±	4.60
[72]	Wheat straw—15 years stove	TSP	17.00	±	7.00
[72]	Rape straw—15 years stove	TSP	13.00	±	5.00
[72]	Rice straw—15 years stove	TSP	8.20	±	2.80
[72]	Cotton straw—15 years stove	TSP	10.00	±	4.0
Average:			**8.03**	±	**3.57**

Residential burning of biomass is not well established, from the point of view of emissions [27].

Sutar et al. [25] reported that the during biomass combustion, there is drying and heating of the fuel, pyrolysis and the emission of volatiles and char formation. Volatiles combustion is in the flaming phase, and char combustion in the smoldering phase. Generally, there are higher emissions during smoldering combustion, where there is a lack of air for complete combustion [27,65].

Eastern white pine and red oak were burned in a woodstove, in experiments by Butcher and Sorenson [70]. The authors determined the emission factor of total particles in a series of experimental conditions. Emission factors varied from 1.27 to 24.35 g/kg.

Butcher and Ellenbecker [69] evaluated emissions of particles larger than 4 µm during combustion of red oak and eastern hemlock trees in residential heaters. The authors found emission factors varying from 1.6 to 6.4 g/kg.

Hossain et al. [44] studied size distribution in number of ultrafine particles and their volatility during the burning of oak (hardwood), pine (softwood), and rice straw. The biomass was burned in a commercial stove. Flame and smoldering combustion phases were analyzed. Rice straw was also burned outside in open air. The chimney was connected to a dilution tunnel.

Controlled burning experiments were conducted in the studies by Shen et al. [71]. Their objective was to evaluate the influence of air supply, fuel mass load and burning rate on PM emissions, elemental carbon and organic carbon, as well as PM size distribution. Corn straw was burned in a cooking stove. The gas sample was diluted and TSP was stored in a quartz fiber filter. Average EF PM was 3.84 ± 1.02 g/kg.

In the studies by Schmidl et al. [73], four species of hardwood and softwood briquettes were burned in a heating stove. PM samples with diameter higher than 10 μm were collected and analyzed to obtain the aerosol chemical profile. Upon leaving the chimney, air samples were diluted and then conducted through a single stage impactor, which retains PM with diameters higher than 10 μm.

Effect of moisture, fuel charge size, air ventilation and feeding rate on EF and PM size distribution were evaluated in the studies done by Shen et al. [45]. The authors used wood as fuel. Burning experiments were done in a woodstove.

Tissari et al. [27] conducted their burning experiments in a conventional masonry heater. Birch wood was used as a fuel in this heater. The authors evaluated gas and particle emissions in normal and smoldering combustion. Before measurements, air flow from the sample was diluted in a dilution tunnel. Emissions of particles in number and size distribution in number and mass were measured in real time. The authors verified that in the smoldering combustion, PM_1 emissions were six times higher than in normal combustion.

Straw from four types of crop was burned in the experiments by Wei et al. [72]. Burning took place in stoves with similar structures but with different ages. The authors determined the EFs for PM, OC, EC and PAH. Their goal was to analyze the influence of stove age and type of fuel on the emission of pollutant compounds. PM samples were collected in a Chinese residential kitchen. The authors observed that PM emission factor did not vary in a significant manner among the four types of fuel analyzed. However, PM EF was significantly affected by the stove's age. EF for carbon particles in the 15-year-old stove was approximately 2.5 times higher than in the one-year-old stove. For the authors, the increase in the EF for particles of carbon in older stoves occurs by degradation. Wei et al. [72] emphasized that the stove age makes emission variations more complex, and this needs to be considered when estimating future emissions.

EF values were also found in the literature for residential burning of dung (Table 12). Residential burning resulted in an EF for TSP of 4.45 ± 0.42 g/kg.

Table 12. EF values found in the literature for residential burning of dung in natura.

Reference	Fuel	Size	EF PM (g/kg)		
[46]	Dung cake—improve metal stove	TSP	4.90	±	1.60
[46]	Dung cake—improve fired-clay stove	TSP	4.40	±	0.60
[46]	Dung cake—traditional mud stove	TSP	4.60	±	0.60
[46]	Dung cake—improve fired-clay stove	TSP	3.90	±	0.90
Average:			**4.45**	**±**	**0.42**

In the literature, PM emission factors were significantly higher for raw dung cake [6,28,46] and dung briquette combustion [46] than for other fuels.

4.2.3. Laboratory

(a) Compacted Biomass

Brassard et al. [34] studied the burning of compacted biomass in laboratory. In their experiments, biomass includes two dedicated energy crops in the form of pellets, switchgrass and fast-growing willow, and one waste from animal production, the dried solid fraction of pig dung. They also burned wood pellets. Biomass was burned in small scale burners in the laboratory (17.58 kW). Emissions of particles were expressed in mg/m^3. According to the authors, PM emissions were significantly

higher for agricultural biomass than for forest biomass. In addition, PM emissions for pig manure (141 mg/m^3) were higher than for wood (37 mg/m^3), switch grass (39 mg/m^3) and willow (63 mg/m^3).

(b) Biomass in Natura

EF values for forest biomass burning in the laboratory were shown on Table 13. Particles with diameter smaller than 2.5 μm had a more elevated EF than TSP. EF for $PM_{2.5}$ was 18.15 ± 14.36 g/kg, while EF for TSP was 3.93 ± 1.53 g/kg. A high variation in the EF for $PM_{2.5}$ was observed for laboratory burning of forest biomass in natura. Tissari et al. [27] also observed a high variation in the EF for PM during combustion of this biomass. According to the authors, forest biomass has been shown to vary widely and emissions from combustion depend on many factors such as type of burners and species of fuel wood. For Saidur et al. [74], biomass is a sources of energy with very specific properties.

Table 13. EF values found in the literature for laboratory burning of forest biomass in natura.

Reference	Fuel	Size	EF PM (g/kg)		
[50]	Artocarpus altilus	$PM_{2.5}$	16.10	±	_
[50]	Calliandra haematocephala	$PM_{2.5}$	7.50	±	_
[50]	Theobroma cacao	$PM_{2.5}$	2.22	±	_
[50]	Dambo	$PM_{2.5}$	11.40	±	_
[50]	Davidson pruriens	$PM_{2.5}$	7.34	±	_
[50]	Eucalyptus sp.	$PM_{2.5}$	9.87	±	_
[50]	*Ficus* sp. (1)	$PM_{2.5}$	10.40	±	_
[50]	*Ficus* sp. (2)	$PM_{2.5}$	16.30	±	_
[50]	Mango	$PM_{2.5}$	5.81	±	_
[50]	Tropical composite	$PM_{2.5}$	13.50	±	_
[50]	Terminalia catappa	$PM_{2.5}$	16.60	±	_
[50]	Forest—average	$PM_{2.5}$	9.93	±	_
[75]	Montane	$PM_{2.5}$	29.40	±	25.10
[75]	Douglas fir	$PM_{2.5}$	42.90	±	22.90
[75]	Lodgepole pine	$PM_{2.5}$	18.10	±	23.10
[75]	Ponderosa pine	$PM_{2.5}$	27.70	±	26.00
[75]	Rangeland	$PM_{2.5}$	18.90	±	13.90
[75]	Sagebrush	$PM_{2.5}$	29.00	±	1.90
[75]	Chaparral	$PM_{2.5}$	11.60	±	15.10
[75]	Ceanothus	$PM_{2.5}$	7.80	±	1.20
[75]	Chamise	$PM_{2.5}$	6.50	±	4.20
[75]	Manzanita	$PM_{2.5}$	23.50	±	25.90
[75]	Coastal plain	$PM_{2.5}$	23.40	±	18.70
[75]	Black needle rush	$PM_{2.5}$	38.40	±	_
[75]	Common reed	$PM_{2.5}$	36.20	±	_
[75]	Gallberry	$PM_{2.5}$	20.50	±	_
[75]	Hickory	$PM_{2.5}$	12.50	±	_
[75]	Kudzu	$PM_{2.5}$	70.50	±	_
[75]	Longleaf pine	$PM_{2.5}$	38.30	±	13.60
[75]	Oak	$PM_{2.5}$	18.20	±	_
[75]	Palmetto	$PM_{2.5}$	11.40	±	10.50
[75]	Turkey oak	$PM_{2.5}$	52.20	±	_
[75]	Wax myrtle	$PM_{2.5}$	12.20	±	4.00
[75]	Boreal forest	$PM_{2.5}$	12.70	±	11.30
[75]	Alaskan duff	$PM_{2.5}$	16.10	±	15.90
[75]	Black spruce	$PM_{2.5}$	10.40	±	4.20
[75]	White spruce	$PM_{2.5}$	5.90	±	_
[75]	Other	$PM_{2.5}$	10.20	±	6.60
[75]	Fern	$PM_{2.5}$	3.90	±	_
[30]	Amazon biomass	$PM_{2.5}$	3.18	±	1.35
[30]	Araucaria biomass	$PM_{2.5}$	5.66	±	1.03

Table 13. *Cont.*

Reference	Fuel	Size	EF PM (g/kg)		
Average:			**18.15**	±	**14.36**
[6]	Fuel wood	TSP	4.34	±	1.06
[28]	Guava	TSP	3.08	±	0.29
[28]	Eucalyptus	TSP	3.93	±	0.46
[28]	Acacia	TSP	6.06	±	1.26
[28]	Neem	TSP	5.84	±	1.26
[28]	Mulberry	TSP	2.45	±	0.38
[28]	Indian rosewood	TSP	4.02	±	0.54
[33]	Fuel wood	TSP	1.69	±	0.98
Average:			**3.93**	±	**1.53**

The average EFs for agriculture and garden biomass burned in laboratory were 4.90 ± 3.34 g/kg, 11.64 ± 6.94 g/kg, and 9.31 ± 8.59 g/kg, for $PM_{2.5}$, $PM_{10–2.5}$ and TSP, respectively. Table 14 details the values of the literature for such parameters for different types of fuels.

Table 14. EF values found in the literature for laboratory burning of agricultural and garden biomass in natura.

Reference	Fuel	Size	EF PM (g/kg)		
[50]	Sugar cane	$PM_{2.5}$	2.17	±	_
[75]	Juniper	$PM_{2.5}$	4.20	±	_
[75]	Rabbitbrush	$PM_{2.5}$	3.40	±	_
[75]	Rhododendron	$PM_{2.5}$	3.70	±	_
[75]	Wiregrass	$PM_{2.5}$	6.40	±	_
[75]	Rice straw—flaming	$PM_{2.5}$	11.80	±	6.50
[37]	Sugar cane—flaming	$PM_{2.5}$	2.60	±	1.60
[76]	Rice straw (MC—5%)	$PM_{2.5}$	5.86	±	1.85
[76]	Rice straw (MC—10%)	$PM_{2.5}$	8.66	±	2.29
[76]	Rice straw (MC—20%)	$PM_{2.5}$	20.67	±	3.88
Average:			**6.95**	±	**5.66**
[76]	Rice straw (MC—5%)	$PM_{10-2.5}$	5.56	±	1.71
[76]	Rice straw (MC—%)	$PM_{10-2.5}$	8.90	±	2.39
[76]	Rice straw (MC—20%)	$PM_{10-2.5}$	20.17	±	4.43
Average:			**11.54**	±	**7.66**
[6]	Crop residue	TSP	7.54	±	4.17
[6]	Rice straw—pile	TSP	20.10	±	7.70
[6]	Rice straw—spread	TSP	4.70	±	2.20
[28]	Pigeon pea	TSP	2.75	±	0.30
[28]	Maize	TSP	5.64	±	1.26
[28]	Cotton	TSP	3.58	±	0.61
[28]	Prickly sesban	TSP	4.03	±	0.78
[28]	Mustard stem	TSP	7.43	±	1.31
[76]	Rice straw (MC—5%)	TSP	8.41	±	4.52
[76]	Rice straw (MC—10%)	TSP	14.26	±	3.23
[76]	Rice straw (MC—20%)	TSP	31.09	±	11.79
[33]	Agriculture residue	TSP	2.15	±	1.00
Average:			**9.31**	±	**8.59**

MC—Moisture content.

According to the results found in the literature (Table 13), during laboratory burning of biomass in natura, forest biomass tends to release mainly fine particles. Agricultural and garden biomass

(Table 14) tends to release mainly coarse particles. In addition, emissions are highest in dung followed by agriculture residues and wood biomass [6,28].

In laboratory studies, special attention has been given to the variation of emissions of particulate matter during the combustion phases (ignition, flame, intermediate and smoldering) [6,11,29,30,54,76]. Wardoyo et al. [11] noted that particle diameter varied according to the burning phase. For some authors [29,30,37,54], the particle concentration are higher during the flame phase and decreased gradually in the mixed and smoldering phases. On the other hand, Hossain et al. [44], Amaral et al. [30] and Costa et al. [54] observed that $PM_{2.5}$ diameter tended to increase with the combustion progress. According to Hossain et al. [44], larger diameters in the smoldering phase might be associated with condensation of volatile organic compounds on the particle as the temperature drops. Wardoyo et al. [11], Hosseini et al. [29] and França et al. [37], however, observed that the particle diameter was higher during the flame phase than in the smoldering phase. For França et al. [37], the emission of larger particles in the flame phase takes place because the fires are intense, due to the low moisture content of the sample.

Emissions of gases and $PM_{2.5}$ were evaluated in the studies by Amaral et al. [30] for the Brazilian hardwood and softwood biomass. The authors compared results for emission factor, diameter, and $PM_{2.5}$ concentration, in terms of flame and smoldering combustion phases. Maximum $PM_{2.5}$ concentrations were observed in the flame phase. Araucaria biomass emitted larger particles at a higher concentration than Amazon biomass. In Brazil, Costa et al. [54] burned Amazon biomass in laboratory to determine $PM_{2.5}$ and PM_{10}. Their results were presented for particle size and concentration (mg/m^3).

Yokelson et al. [50] also analyzed $PM_{2.5}$ emission factor from burning tropical forests and other vegetation, in Brazil. Data resulted from laboratory experiments (October 2003) and burning campaigns in the Amazon during the dry season (2004), which involved aircraft and soil monitoring. EF from burning experiments in the laboratory was coupled with EF obtained during the Tropical Forest and Fire Emissions Experiment. EF of $PM_{2.5}$ was 14.8 g/kg for primary deforestation burning and 18.7 g/kg for pasture maintenance burning.

Saud et al. [28] determined PM emission factor for three categories of fuel biomass commonly used in the North of India: Agricultural residues, fuel wood and dung cake. Emissions for PM, EC, OC and soluble ions were evaluated. PM samples went through a dilution tunnel. Among these three categories of biomass fuel, dung cake had the highest PM emission (15.68 ± 0.70 g/kg), followed by agricultural residues (5.24 ± 0.60 g/kg) and wood fuel (4.68 ± 0.47 g/kg). Analyses done in the studies by Sen et al. [33] were similar to those by Saud et al. [28]. However, Sen et al. [33] evaluated biomass from the West of India and included a study of gas pollutants.

Sanchis et al. [76] evaluated the effect of moisture content in rice straw (5%, 10% and 20%) in the emission factor of CO_2 and of different particle sizes. The results considered the flame and smoldering combustion phases. The authors noted that the burning time increased with increasing fuel humidity level. This occurred for both phases evaluated. $PM_{2.5}$ was responsible for more than 60% of the total PM mass.

McMeeking et al. [75] characterized gas emissions and particles from 33 plant species, during 255 controlled burns. Results were presented in terms of emission factor (g/kg) and concentration of PM_{10} and $PM_{2.5}$ ($\mu g/m^3$).

Hosseini et al. [29] evaluated PM size distribution in fires from eight forest species in the Southeast of the United States. Particle size distribution was as expected for the flaming, mixed and smoldering combustion phases. Sample flow was diluted.

Pozza et al. [77] burned sugarcane straw in the laboratory and in the field. The objective of these authors was to determine the chemical elements that make up PM. Particles from the coarse fraction (PM_{10}–$PM_{2.5}$) and fine fraction ($PM_{2.5}$) were collected. França et al. [37] as well as Pozza et al. [77] evaluated emissions from burning sugarcane straw. França et al. [37] determined emission factors for some gases and $PM_{2.5}$. A dilution agent was employed in the study. Estimated average value for $PM_{2.5}$ emission factor was 2.6 ± 1.6 g/kg.

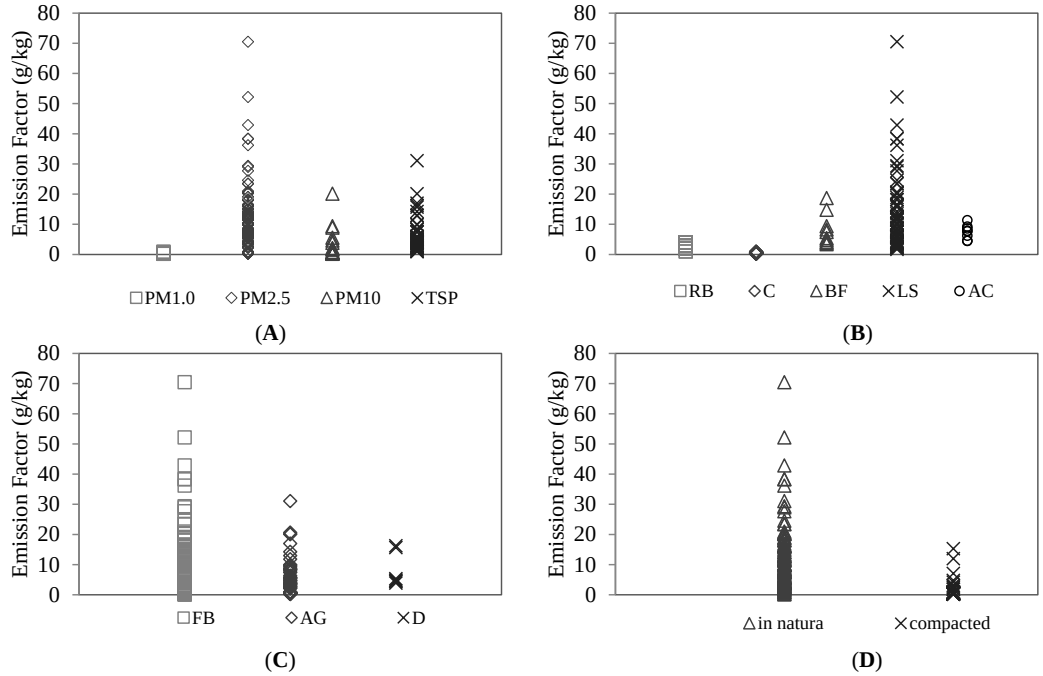
EF values found in the literature for laboratory burning of dung in natura were presented on Table 15. For this biomass, the EF for TSP was 12.44 ± 6.13 g/kg.

Table 15. EF values found in the literature for laboratory burning of dung in natura.

Reference	Fuel	Size	EF PM (g/kg)		
[6]	Dung cake	TSP	16.26	±	2.29
[28]	Dung cake	TSP	15.68	±	0.70
[33]	Dung cake	TSP	5.37	±	3.90
Average:			**12.44**	±	**6.13**

5. Discussion

Among the particle size ranges analyzed in this review work, fine particles ($PM_{2.5}$) had higher emission factors than the other size ranges (Figure 1A). The overall average emission factors were 12.35 ± 11.31, 6.31 ± 5.55, 3.32 ± 4.97 and 0.48 ± 0.21 g/kg, for $PM_{2.5}$, TSP, PM_{10} and PM_1, respectively. In the literature, the emission factor has been employed mainly to quantify $PM_{2.5}$. These values have varied widely. This variation may be due to biomass type, burning location, degree of compactness of the fuel, measurement equipment, fuel moisture content, flow dilution, and other factors.



RB- Residential burning; C- Combustor; BF- Burning field; LS- Laboratory sampling; AC- Aircraft; FB- Forest biomass; AG- Agricultural and garden biomass; D- Dung.

Figure 1. Particulate matter emission factors found in the literature: (**A**) size range; (**B**) sampling environment; (**C**) biomass type; and (**D**) biomass densification.

When sampling environment was considered, emission factors were higher for burning conducted in the laboratory, followed by field burning, residences and combustors (Figure 1B). Lemieux et al. [20] also observed that open burning emissions are higher than emissions from well controlled combustion sources. Average emission factors for $PM_{2.5}$ were 16.12 ± 13.74, 11.80 ± 6.05, 11.19 ± 4.86 and 0.55 ± 0.21 g/kg, for laboratory, field, residential burning and combustors, respectively.

During burning of forest biomass in natura, overall average EFs, regardless of PM size, were 16.00 ± 14.07 g/kg, 8.26 ± 5.98 g/kg, and 8.18 ± 6.10 g/kg, for laboratory, residential burning and

field, respectively. When compacted forest biomass was subjected to burning, overall average EFs were 4.90 ± 5.46 g/kg and 0.32 ± 0.09 g/kg, for residential and combustor burning, respectively. EF in residential burners are higher than those in industrial combustors due to the low combustion efficiency of residential burners [72]. For Wei et al. [72], low combustion efficiency leads to emission of a series of incomplete products, such as PM, OC, EC, and polycyclic aromatic hydrocarbons.

Particle emissions, in residential burning can also be affected by the age of the stove that is employed. Wei et al. [72] observed that EF in a 15-year-old stove, was approximately 2.5 times higher than in the one–year-old stove. For the authors, the increase in the EF for carbon particles in older stoves can be explained by the stove degradation. Wei et al. [72] emphasized that the stove age makes emission variations more complex, and this needs to be considered when estimating future emissions. Despite the fact that the traditional stove has high pollutant emissions, better results can be obtained if improved stoves are employed [46]. In addition, Gonçalves et al. [67] observed that emission factors for fine particles from burning in woodstoves were lower to those in fireplaces.

Different types of biomass presented different emissions levels. In forest burning, the overall average emission factor (10.70 ± 11.09 g/kg) was higher than for dung (7.45 ± 5.28 g/kg), and for agricultural and garden biomasses (5.02 ± 6.02 g/kg). Some authors [6,28,34,41,46] found that PM emission factors were higher in dung, followed by agricultural residues and wood biomass. Possibly, higher FE values for PM, in forest biomass have occurred due to high variety of species cited in this work, which included species from North and South America, Asia and Europe.

Combustion of compacted biomass resulted in lower emission factors (1.67 ± 3.01 g/kg) than biomass in natura (10.72 ± 9.93 g/kg) (Figure 1D), as well as related by Shen et al. [41]. Compacting biomass offers an alternative that reduces atmospheric pollution from emission of particles in the environment. In their study, Chandrasekaran et al. [63] suggested cultivation of grass as an alternative fuel in areas that are not appropriate for food production. According to the authors, these types of biomass grow quickly and are ideal crops for use as energy since they require minimum care. After harvesting the biomass can be compacted as pellets. When compacted, grasses have energetic content similar to wood, but have the advantage of allowing many harvests per year.

Among the different types of biomass analyzed, forest biomass in natura had the highest EF for $PM_{2.5}$ of 15.73 ± 11.60 g/kg, followed by agricultural and garden biomasses in natura (6.93 ± 5.16 g/kg), compacted forest biomass (5.61 ± 6.14 g/kg), and compacted agricultural and garden biomass (0.61 ± 0.17 g/kg).

EF for PM_{10} was highest in agricultural and garden biomass in natura (8.75 ± 6.03 g/kg), followed by forest biomass in natura (1.85 ± 0.36 g/kg), compacted forest biomass (0.66 ± 0.67 g/kg), and compacted agricultural and garden biomass (0.61 ± 0.22 g/kg). For compacted biomass, Chandrasekaran et al. [63] observed that PM_{10} emissions from combustion of grass pellets were higher than those from wood pellets. Tissari et al. [36] did not find significant differences between cereal based fuels and wood fuels, for PM_1 emissions.

EFs for TSP were 9.21 ± 7.07 g/kg, 7.87 ± 5.55 g/kg, 4.15 ± 2.74 g/kg, 3.32 ± 0.22 g/kg, and 1.49 ± 0.60 g/kg, for agricultural and garden biomass in natura, dung, forest biomass in natura, compacted agricultural and garden biomass, and compacted forest biomass, respectively.

Higher PM_{10} and TSP emission factors seem to be associated with burning of agricultural and garden biomass, while $PM_{2.5}$ emissions seem to predominate in forest biomass burning. Gonçalves et al. [1] pointed out that wood burning is one of the highest sources of fine particle emission in Portugal. However, Shen et al. [71] observed that, during corn straw burning, the emission of fine particles was predominant.

Not many studies have evaluated emissions from compacted biomass. Shen et al. [41] emphasized the need for more studies regarding PM emissions from pellet burning. According to the authors, this measure could confirm if pellet burning really emits less pollutant than other fuels. In addition to pellet emissions, emissions from briquette burning should also be studied. Njenga et al. [31] observed that the briquette produced from charcoal powder reduces Greenhouse Gases emissions. In addition,

it is an alternative fuel, which improves energy security. When assessing the environmental impacts from the use of pellets and briquettes, Murphy et al. [78] realized that pellets requires more energy than briquettes, hence there are higher environmental impacts. Thus, the use of briquettes as fuel can be a better alternative than pellets.

Most of the EFs found in the literature and reported in this study considered laboratory and residential biomass burning. This is because sampling in the field is significantly more difficult and expensive than in laboratory and residential tests. Moreover, in some countries such as Brazil, the forest burning is allowed only in limited areas (maximum 4 hectares), and it requires authorization [79].

There was a large variation of PM EF in this review, especially for forest biomass, such as reported by Tissari et al. [27]. For Carvalho et al. [79], the burning process and the manner in which the fuel is distributed on the ground in a forest fire can increase the percentage of fine biomass prior to the burn and influence emission rates. Lemieux et al. [20] emphasized that burning conditions can significantly alter emission levels, especially in residential burners [27]. According to Tissari et al. [27], in good combustion conditions, the quantity of air is enough and process temperature is high. Secondary heated air in the superior part of the combustion chamber and a good mixture of air and secondary flue gases can improve ignition of hydrocarbons, resulting in low emission of pollutants. Therefore, in good combustion conditions, emission of fine particles is mainly due to vaporization of elements that make up the ashes from wood fuel. Temperature also has an important affect on vaporization; in such a way that larger amount of fine ash is released at higher temperatures.

EF is dependent on different parameters, such as fuel characteristics [27,50]. Biomass is characterized by large variations in its properties than for other fuels [74]. For example, the fuel moisture content can exert great influence on EF [76]. According to the authors, higher moisture content causes incomplete combustion, thus altering emissions depending on fuel humidity. PM emission factor can increase with increasing fuel moisture content [45]. For rice straw burning, Sanchis et al. [76] suggested that combustion must be done after drying the straw with very little humidity in the air in order to reduce levels of pollutant emission. According to França et al. [37], the low moisture content of the biomass sample generates an increase in fire intensity, and as a consequence fine particles are emitted at a higher concentration.

Emissions and the particle size can also vary with the combustion phase. Some authors have found that PM emissions are higher in the intermediate and smoldering combustion phases [27,65]. However, Hosseini et al. [29] and Amaral et al. [30] noted that the particle concentration was higher during the flame phase and decreased gradually in the intermediate and smoldering phases. Fine particles have been observed in the flaming phase [30,65].

Butcher and Ellenbecker [69] found that EF was dependent from fuel load and emission factor increases when load increases. Others authors have not found relation between load and PM EF [45,71].

Another factor that can influence PM emissions measurements is the sampling method. According to Amaral et al. [80], particle measurements can significantly vary, even those taken in the same place and for the same material. Variation occurs mainly due to equipment characteristics and sampling procedures. Sample dilution can also affect the measured values. According to França et al. [37], dilution is important because it prevents saturation and improves the measurements, as the particles become more dispersed. That way, overestimated results are avoided.

6. Conclusions

The knowledge of particulate matter emission factors is important for the development of strategies for pollution control and for the assessment of the practicability of burning a determined fuel. Emission factors are also important as parameters for studies of particle effects on human health and on climate change. In this review article, several sources of particulate matter were considered, and the emission factors from different types of biomass, sampling environments, PM sizes and biomass degree of compactness were compared. Combustion of compacted biomass resulted in lower emission factors than biomass in natura. $PM_{2.5}$ emission factors tended to be higher than at other size ranges. Higher

emissions for PM_{10} and TSP were associated with burning of agricultural and garden biomass, while $PM_{2.5}$ emissions were predominant in forest biomass burning. The location of the experiment also affects results: emission factors are highest in laboratory, followed by field, residences and combustors.

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