atmosphere

MDPI

Article

A Comparative Study of Stack Emissions from Straight-Line and Zigzag Brick Kilns in Nepal

Sangeet Nepal [1,2], Parth Sarathi Mahapatra [1], Sagar Adhikari [1], Sujan Shrestha [1,3], Prakash Sharma [2], Kundan Lal Shrestha [2], Bidya Banmali Pradhan [1] and Siva Praveen Puppala [1,*]

[1] International Centre for Integrated Mountain Development (ICIMOD), G.P.O. Box 3226, Kathmandu 44700, Nepal; Sangeet.Nepal@icimod.org (S.N.); parth.mahapatra@icimod.org (P.S.M.); Sagar.Adhikari@icimod.org (S.A.); sujanshrestha101@gmail.com (S.S.); Bidya.Pradhan@icimod.org (B.B.P.)

[2] Department of Environmental Science and Engineering, Kathmandu University, Dhulikhel 45200, Nepal; prakash.sharma7574@gmail.com (P.S.); kundan@ku.edu.np (K.L.S.)

[3] Department of Environmental Science, Baylor University, Waco, TX 76706, USA

* Correspondence: SivaPraveen.Puppala@icimod.org; Tel.: +977-1-527-5222

Received: 21 December 2018; Accepted: 22 January 2019; Published: 1 March 2019

check for updates

Abstract: Nepal has approximately 1000 operational brick kilns, which contribute significantly to ambient air pollution. They also account for 1.81% of the total bricks produced in the South Asian region. Little is known about their emissions, which are consequently not represented in regional/global emission inventories. This study compared emissions from seven brick kilns. Four were Fixed Chimney Bull's Trench Kilns (FCBTKs) and three were Induced-Draught Zigzag Kilns (IDZKs). The concentrations of carbon dioxide (CO_2), sulfur dioxide (SO_2), black carbon (BC), and particulate matter (PM) with a diameter less than 2.5 µm ($PM_{2.5}$) were measured. The respective emission factors (EFs) were estimated using the carbon mass balance method. The average fuel-based EF for CO_2, SO_2, $PM_{2.5}$, and BC were estimated as 1633 ± 134, 22 ± 22, 3.8 ± 2.6 and 0.6 ± 0.2 g per kg, respectively, for all FCBTKs. Those for IDZKs were 1981 ± 232, 24 ± 22, 3.1 ± 1, and 0.4 ± 0.2 g per kg, respectively. Overall, the study found that converting the technology from straight-line kilns to zigzag kilns can reduce $PM_{2.5}$ emissions by ~20% and BC emissions by ~30%, based on emission factor estimates of per kilogram of fuel. While considering per kilogram of fired brick, emission reductions were approximately 40% for $PM_{2.5}$ and 55% for BC, but this definitely depends on proper stacking and firing procedures.

Keywords: air pollution; brick kiln; South Asia; emission factor; gaseous pollutant; particulate pollutants

1. Introduction

In the majority of low–middle-income countries, brick kilns are one of the small-scale industries that are a prominent source of ambient air pollution, but which are often overlooked [1,2]. With the rapid increase in urbanization and development, the demand for brick production is also rising. However, lack of sound knowledge about the emissions from such sources often hinders the design of proper mitigation strategies and better representation in regional and global emission inventories [3,4]. There have been clear, adverse health outcomes in populations residing in the immediate vicinity of the kilns [5]. In the context of Nepal, brick production rate has increased sharply by 87.5% between 2009 and 2012 [6,7]. At present, approximately 1000 brick kilns are operational in different parts of the country; these produce 6 billion bricks annually, representing 1.81% of all bricks produced in South Asia [7,8]. Brick kilns in Nepal use approximately 30% of total coal consumption in the industrial sector [6,9]. It is important to understand the contribution of brick kilns to the load of ambient air pollution in the context of cities such as the capital of Nepal, Kathmandu. Kim et al. [1] used a source apportionment method and found that brick kilns contributed 40% of elemental carbon (EC) to the particulate matter less than 10 μm diameter (PM_{10}) load in the Kathmandu Valley. Another study conducted during winter (2012–13) by Sarkar et al. suggested that approximately 10.4% of non-methane volatile organic compounds (NMVOCs) were contributed by biomass co-fired brick kilns [10].

The emissions from the brick kilns primarily depend on the type of fuel and the technology used for brick firing. Approximately 1.2% of global anthropogenic carbon dioxide (CO_2) emissions are contributed to by burning coal to fire bricks [11]. Most of the brick kilns in Nepal use coal as the primary fuel, along with a mixture of other biomass fuels, including bagasse, rice husk, and charcoal. Most kilns are fixed chimney bull's trench kilns (FCBTKs) and zigzag kilns; these represent approximately 70% and 30%, respectively, of all kilns [12]. There are also a few clamp kilns, but official estimates of their numbers are not yet available. Of the FCBTKs and induced-draught zigzag kilns (IDZKs), the latter are expected to be efficient in terms of reduced emissions because of their improved technical aspects. This hypothesis, however, has yet to be validated based on measurements that provide concrete evidence. In addition, brick kilns in developing countries are not tightly regulated or monitored, creating considerable uncertainty about emissions between kilns [13]. Given the prevalence of brick kilns in the region, emissions not only contribute to local air quality, but also add to the transport of pollutants to the surrounding Himalayan ecosystem. In order to overcome the challenge of providing recent and regionally representative emission estimates of underrepresented emission sources, it is vital to perform emission measurements of these sources.

In the recent past, only two brick kilns (one zigzag kiln and one clamp kiln) have been monitored in Nepal: this took place during the Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE) in April 2015 [14,15]. Results from this study, though, provided an initial indication of the differences in emissions from traditional and modified kilns, but the small sample size (n = 2) meant that more definitive comparisons could not be made. To provide more information, we designed a study of seven different kilns (four FCBTKs and three IDZKs) distributed across the central and western regions of Nepal. We quantified the emissions and, subsequently, the emission factors for CO_2, sulfur dioxide (SO_2), black carbon (BC), and particulate matter (PM) of less than 2.5 μm diameter ($PM_{2.5}$) based on the activity rate.

2. Site Description

The brick kiln emission measurement study was conducted between 29 April and 5 May 2017 in the Lalitpur district of Kathmandu Valley (central Nepal), and between 24 May and 1 June 2017 in Kailali and Kanchanpur districts (western Nepal) (Figure 1).

The Kathmandu Valley is a broad, flat, bowl-shaped structure, with a valley floor of ~340 km^2 and an altitude of 1300 m above sea level (masl) [16]. It is surrounded by tall mountains ranging between 2000 and 2800 masl, creating a complex topography around the valley. The valley also has five mountain passes (1500–1550 masl) in the northwestern and southeastern sectors that serve as major pathways for movement of wind carrying pollutants inside or out of the valley. The valley has ~110 brick kilns, which contribute significantly to the deteriorating air quality in the Kathmandu Valley. Currently, almost all kilns have been converted to the IDZ type, but outside the valley FCBTKs predominate. Hence, two IDZKs were measured within the Kathmandu Valley during the campaign.

Emission measurements were also conducted in five kilns (IDZK; n = 1 and FCBTK; n = 4) spread around Kailali and Kanchanpur districts in the western Nepal region. Both districts lie in the lower tropical zone ~700 km from the Kathmandu Valley, and their southern fringes border India (Figure 1a). Kanchanpur has an area of 171.24 km^2 and is located at an altitude of around 229 masl; Kailali has an area of 3235 km^2 and is located at an altitude of around 109–1950 masl.

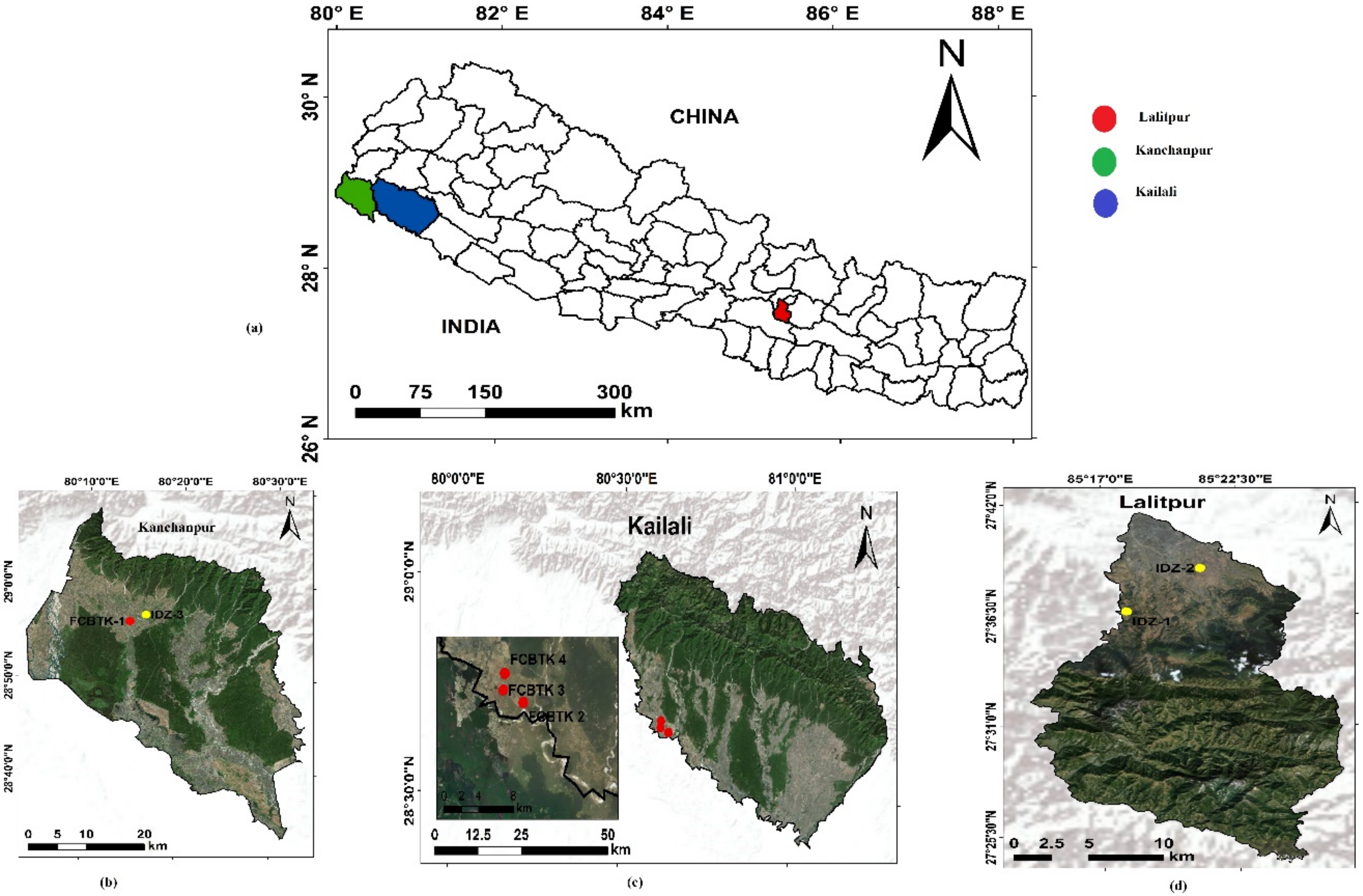

Figure 1. Study location: (**a**) map of Nepal indicating Kanchanpur (green patch), Kailali (blue patch), and Lalitpur districts (red patch); (**b**) expanded view of Kanchanpur district; (**c**) expanded view of Kailali district; and (**d**) expanded view of Lalitpur district, with dots representing the location of kilns. The red dots denote FCBTKs (fixed chimney bull's trench kilns) and yellow dots indicate IDZKs (induced-draught zigzag kilns) measured during the study.

3. General Description of the Brick Kilns

Brick kilns (moving fire continuous kilns found in Nepal) are divided into two broad categories, based on their design: (1) the traditional FCBTK; and (2) the modern improved zigzag.

FCBTK is a moving fire kiln in which the fire moves in a straight path through the gaps made by the stacking pattern of green (unbaked) bricks. They are stacked in the annular space between the outer and inner wall of the kiln. The green bricks are stacked in front of the firing zone, and fired bricks are removed from the rear part (cooling zone). This is a natural draught kiln in which the chimney creates the draught necessary for the combustion process. Cold air enters through the gaps made by the stacking of the fired bricks in the cooling zone, bringing down the temperature of fired bricks and subsequently increasing the air temperature in the firing zone. The heated air moves towards the firing zone, thereby providing the necessary excess air for the combustion process and moves upwards through the duct to the chimney (Figure 2).

The IDZK is also a moving fire kiln in which the fire moves in a zigzag path through the gaps made by the stacking pattern of green bricks. The necessary draught required for combustion is provided by a fan. The structure of the IDZK is similar to that of the FCBTK, but has some differences: (1) the stacking pattern of the unbaked bricks; and (2) a slight modification from the oval-shaped outer and inner walls to a rectangular shape. The cooling zone, firing zone, and preheating zone are the same in both kilns. The zigzag fire path or a prolonged fire path favors steady heat transfer of the air to the brick, providing conducive conditions for combustion and, so, reducing fuel combustion. The improved stacking pattern also helps in the scavenging of particulates on the walls. Hence, overall proper feeding of the coal in smaller quantities and frequent diversion of the flue gas (due to the zigzag course of the fire path in IDZKs) creates a turbulent air flow that allows proper combustion and subsequent scavenging of the particulates on the wall. This should generally lead to lower fuel consumption and reduced emissions of $PM_{2.5}$ in the IDZKs (Figure 2).

In general, fewer bricks are produced per day from a FCBTK than from an IDZK. The mean weight of bricks manufactured from FCBTK and IDZK kilns measured in the present study were ~2.4 and ~1.9 kg, respectively, during the measurement days (Table 1).

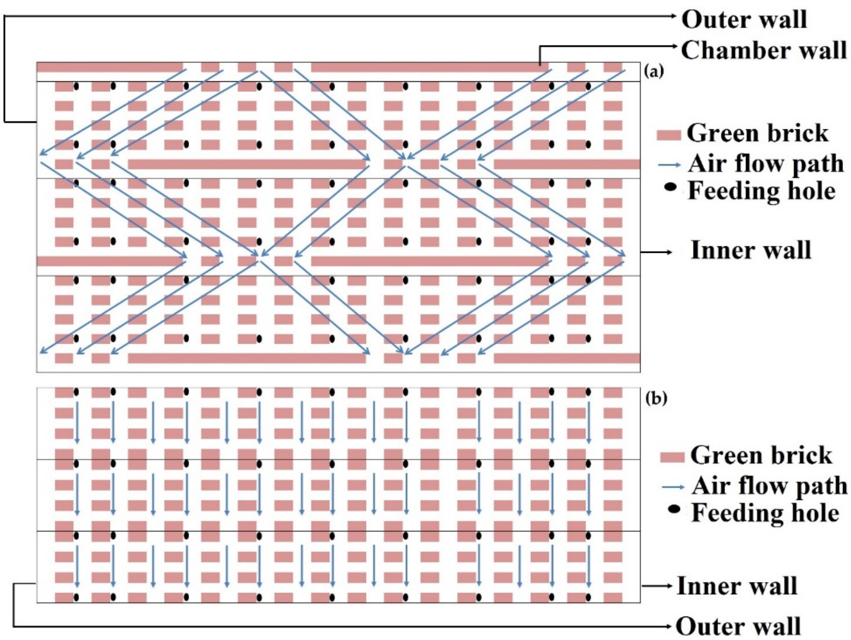

Figure 2. Illustration of stacking pattern of green bricks and air flow in (**a**) IDZKs and (**b**) FCBTKs; The pink color denote green bricks, blue arrows denote flow of air, and black circles denote feeding holes.

Table 1. Details about the kilns measured (including location, capacity, fuel used) and results of fuel analysis and specific energy consumption.

Kilns	Location	Total Bricks Produced per Day	Weight per Brick (kg)	Total Fuel Consumption per Day (kg)	Fuel Used	Carbon Content (%)	Sulfur (%)	Gross Calorific Value (MJ/kg)	SEC (MJ/kg)
FCBTK1	Sundarpur, Kanchanpur	30,000	2.49	4000	Coal (90%), rice husk (10%)	40.68	4.6	21.86	1.17
FCBTK2	Jugada gaun, Kailali	34,000	2.42	5680	Coal and sawdust (70%), rice husk (30%)	50.54	2.21	20.46	1.04
FCBTK3	Ghuiya ghat, Kailali	35,000	2.57	6504	Briquette (100%)	45.21	0.01	16.46	1.19
FCBTK4	Jugada gaun, Kailali	31,000	2.25	4064	Coal (40%), rice husk (60%)	45.44	1.35	16.90	0.99
IDZK1	Bungmati, Lalitpur	84,000	1.9	4652	Coal (100%)	59.02	3.14	20.77	0.60
IDZK2	Imadol, Lalitpur	60,000	1.7	4500	Coal (100%)	59.02	3.14	20.77	0.91
IDZK3	Sankarpur, Kanchanpur	62,000	2.21	7040	Rice husk (25%), Coal and rice husk (32%), coal (43%)	47.49	2.86	19.50	1.06

SEC = specific energy consumption (MJ/kg of fired product).

4. Past Research in the South Asian Region and Elsewhere

Brick kilns present in the South Asian region have similarity with respect to their technical attributes and mode of operations [17]. To provide a global perspective on emission factors (EFs) (based on per kilogram of fuel used and per kilogram of fired brick produced) and real time concentration of different pollutants from brick kilns, prior research from China, India, Bangladesh, Nepal, Vietnam, Mexico, and South Africa were compared together (Tables 2–7). However, any such comparison with kilns operating in Pakistan was not possible in this instance, due to absence of emission measurements in the country. Overall, the kilns are broadly categorized as traditional and improved brick kilns in accordance to their technology, thus indicating the requirement of measurements in nearby regions. FCBTK, clamp, batch-style, traditional-campaign, traditional-fixed, and traditional-improved kilns are categorized as traditional kilns, while IDZ, Hoffman, tunnel, VSBK (vertical shaft brick kiln), DDK (down draught kiln), model, and MK2 (namely double dome version of Marquez) kilns are categorized as improved ones. Fuel-based emission factors among the kilns within and outside the country for both traditional and improved kilns are quite comparable for the measured pollutants and do not depict any significant difference, although comparison between traditional and improved kilns in the same region suggest the use of improved design of kilns and better kiln management practices to reduce the emission of different pollutants.

5. Materials and Methods

5.1. Stack Sampling

In Nepal, the total height of a brick kiln chimney varies from 20 to 30 m. Considering the individual height of the chimney under measurements, a sample porthole (minimum 10 cm diameter) was made in the stack wall at a height of 10–15 m from the ground following BIS (Bureau of Indian Standards)/US EPA (United States Environmental Protection Agency) guidelines [8,18]. With respect to the latter, scaffolding was prepared with space to sit and mount the instruments at a height of at least 1 m below the porthole. This provided enough space for at least two researchers to work, along with space for safe storage and operation of the equipment. We conducted 6 h of continuous in-stack sampling to measure the real-time concentrations of particulate and gaseous pollutants. This time period covers several cycles of fuel feeding and non-feeding stages. For isokinetic stack sampling, a probe was inserted in the porthole to collect the representative sample by maintaining the velocity inside the nozzle the same as the stack velocity [19]. The average stack velocity in FCBTKs was 0.9 m/s (ranging from 0.5 to 1.1 m/s), and in IDZKs was 1.1 m/s (ranging from 0.47 to 1.6 m/s). In order to perform isokinetic sampling, an 'S-type pitot tube' was used to measure the air flow in the stack (Figure 3). This helped in maintaining the flow in the sampling probe similar to the stack flow.

5.2. Instrumentation

The Ratnoze1 (Mountain Air Engineering, USA) portable sampling system was used to measure the real-time concentrations of particulate and gaseous pollutants from the stack of the brick kilns (Figure 3) [20]. The equipment measures concentrations of CO_2, CO, SO_2, and BC along with PM mass-scattering coefficient. The PM mass was determined gravimetrically using filter papers. This was then converted to the real-time PM mass using the PM mass-scattering coefficient. The BC values are measured using a microAeth (AE-51, AethLabs, CA), that is installed inside the Ratnoze1. Once the attenuation value in the equipment reaches 120 (gets saturated), the data collected thereafter would not be useful. Hence, the microAeth has to be turned off, the filter paper has to be replaced, and then the instrument has to be restarted. In this process, some-time is lost. Normally, the attenuation value reaches 120 at some period during the feeding process due to high amount of emissions (discussed in Section 6.1). Hence, a full feeding cycle was not recorded at any moment of time. The background concentrations of CO_2, CO, and SO_2 were measured using background sensors and were used for background correction. Pre- and post-field calibration and comparison studies were carried out in order to maintain strict quality protocols. More details about the equipment, flow mechanism, and the sensor calibration appear in Adhikari et al. [21]. A flue gas analyzer (E INSTRUMENTS Model E8500 Plus, E Instruments International, LLC, USA) was also used to compare measurements of process variables with those of Ratnoze1.

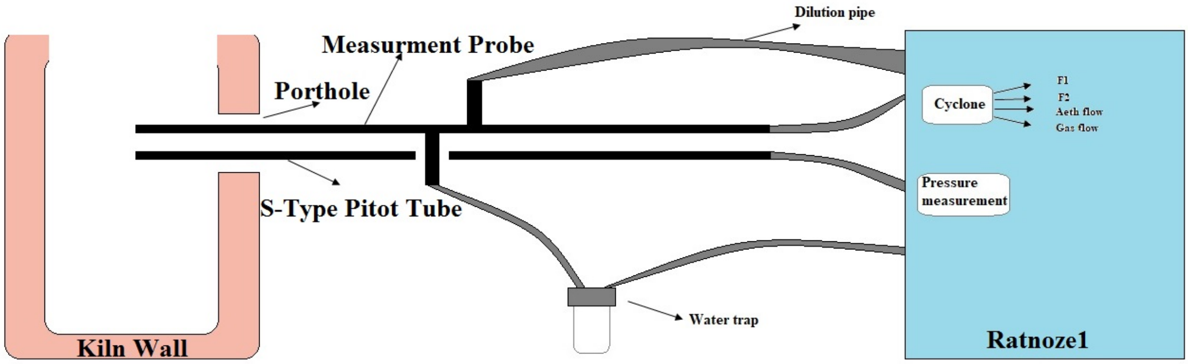

Figure 3. Block diagram of the sampling procedure.

5.3. Fuel Analysis

The proximate and ultimate analyses of the fuel or fuel mixtures obtained from the kilns were conducted at AES Laboratories (P) Ltd., Noida, UP, India, a National Accreditation Board for Testing and Calibration Laboratories (NABL) accredited laboratory certified for chemical testing (T-0176), mechanical testing (T-0719), and biological testing (T-0410). NABL is based on internationally accepted standards and guidelines (ISO/IEC 17025). Results of the fuel analysis appear in Table 1. Proximate analysis of a fuel sample is a weight-based measurement (percentage of the parameters) of moisture, ash, volatile matter, and fixed carbon [22]. Ultimate analysis of the sample is a test to quantify the elementary composition of the individual elements carbon, nitrogen, sulfur, and oxygen [22]. These analyses provide fixed carbon content, total carbon content, and gross calorific value (GCV) of the fuel. For estimating emission factors using the carbon mass balance method, the total carbon content (henceforth stated as carbon content) of the fuel sample was used to calculate the emission factors. Fixed carbon is the weight of solid fuel remaining in a coal sample after volatile matters are distilled off. The fixed carbon does not comprise of the volatile matters such as volatile organic compounds (VOCs), including hydrocarbons which cannot be overlooked for the mass conservation-based carbon balance method. Hence, total carbon content is used for the calculation, which represents the percentage of all forms of carbon present in a fuel sample. Different kinds of fuel/fuel mixtures were used in the kilns measured in the present study. Hence, the fuel/fuel mixture from a majority of the kilns were completely analyzed in the laboratory, while measurements for briquettes [23] and rice husks [24] were obtained from the literature. For the fuel mixture, which could not be measured directly, analysis of individual components in the mixture were derived from the pre-analyzed data/literature, and then translated as per the ratio of their mixing. For example, if there is a fuel mixture XYZ, that is mixed in the ratio 3:2:4, we have the individual analysis for X, Y, and Z. Now we take 33.3% of X, 22.2% of Y, and 44.4% of Z and combine them to get the analysis for XYZ. The fuel analysis values obtained from laboratory analysis or from the literature are used in accordance to the weight-based proportion of the fuel used in the mixture to obtain the final fuel analysis values (Table 1). Henceforth, the individual kiln properties have been discussed under the title FCBTK (1-4) and IDZK (1-3) for the 4 FCBT and 3 IDZ kilns measured in this study.

5.4. Emission Factor per Kilogram of Fuel Used (g/kg Fuel/Fuel Mixture)

The emission factors per kilogram of fuel used were calculated using the standard carbon mass balance method that is based on the principle of carbon mass conservation. A standard set of equations was used to obtain the emission factors [14]; details also appear in Adhikari et al. (under review) [21].

5.5. Emission Factor per Kilogram of Brick Manufactured (g/kg Brick)

In order to calculate the emission factor of pollutants per kilogram of brick manufactured, we used the equation as below (Equation (1)) (Rajarathnam et al. 2014) [8].

$$EF_{kgbrick} = \frac{EF_{fuel} \times SEC}{GCV\ of\ fuel}, \tag{1}$$

where $EF_{kgbrick}$ is the mass production-based emission factor (g/kg brick); EF_{fuel} is the fuel-based emission factor per kilogram of fuel/fuel mixture used (g/kg fuel (fuel mixture)); *GCV* is the gross calorific value or energy content of the fuel/fuel mixture used to fire the brick; and *SEC* is defined as the amount of thermal energy consumed to fire one kilogram of brick (Maithel et al. 2012) [25].

Now, in order to calculate SEC for the individual brick kilns in the present study, the total amount of fuel used and the number of bricks fired during the monitoring period (at least for 6 h for covering multiple feeding and non-feeding cycles) along with the weight of per brick were recorded. Using the total fuel consumed and the total bricks fired during the monitoring period, we derived the amount of fuel used to fire one brick (Equation (2)). Now, using the average weight of one brick, we derived the amount of fuel used to fire one kilogram of unbaked brick (Equation (3)). Finally, to calculate SEC, we multiply the GCV of the fuel determined from the laboratory analysis (Table 1) with the weight of fuel used to fire per kilogram of brick (Equation (4)).

$$\text{Fuel (Fuel Mixture) used to fire one brick} = \frac{\text{Total fuel consumed (kg)}}{\text{Total bricks fired}} \tag{2}$$

$$Fuel\ \text{(Fuel Mixture)}\ used\ to\ fire\ per\ kilogram\ of\ brick = \frac{\text{Fuel used to fire one brick}}{weight\ of\ one\ brick\ (kg)} \tag{3}$$

$$SEC = Fuel\ \text{(Fuel Mixture)}\ used\ to\ fire\ per\ kilogram\ of\ brick \times GCV \tag{4}$$

6. Results and Discussion

6.1. Real-Time Variability of CO_2, SO_2, BC, and $PM_{2.5}$

Emissions of gaseous and particulate pollutants vary during the feeding and non-feeding cycles of FCBTK operation. Real-time temporal profiles of fuel-based emission factors (g/kg) of CO_2, SO_2, BC, and $PM_{2.5}$ are shown in Figure 4 for one particular kiln (FCBTK1). When the fuel is fed (feeding cycle), a rise in concentration of the pollutants (SO_2, BC, and $PM_{2.5}$) can be observed (peaks in the cycle). However, CO_2 emissions fall in magnitude during feeding, while peaks appear during the non-feeding period. When feeding takes place, the combustion process may not have the optimum air–fuel mixture necessary for complete combustion; as a result, peaks in incomplete combustion byproducts, such as BC, $PM_{2.5}$, and some SO_2 are also observed. Overall, the average percentage change in EF_{fuel} for CO_2 was estimated to be ~2% lower during the feeding cycle in comparison to the non-feeding cycle. However, for SO_2, $PM_{2.5}$, and BC, these same byproducts were observed to be higher by 146%, 590%, and 3073%, respectively, during the feeding cycle, compared to the non-feeding cycle. It should also be noted that a feeding cycle only lasts for 5–10 min while non-feeding cycles are much longer in duration. Hence, the percentage increase in the levels of pollutants during the feeding process is only for a few minutes, while 6 h-long continuous sampling is also performed considering these variabilities.

The average concentrations of CO_2, SO_2, $PM_{2.5}$, and BC in normal conditions (25 °C, 1 atm pressure) have been calculated for the seven kilns in the present study (Table 2). Comparative emissions from similar kilns in the region appear in Table 3. The mean concentrations of CO_2 and SO_2 emissions from the FCBTKs in this study (46,175 mg/m^3, 735 mg/m^3, respectively) were observed to be higher in comparison to kilns in Bangladesh and India [18,25]. Comparison of CO_2 and SO_2 emissions from IDZKs (35,639 mg/m^3 and 371 mg/m^3, respectively) in the present study indicates similarity to CO_2 emissions from most Indian kilns [25], but higher than in those from Bangladesh [18] or South

Africa [26]. SO_2 emissions were comparable with those from Bangladeshi kilns [18] but were higher than those in other Indian [25], Vietnamese [27], and South African kilns [26] (except for a VSBK in India). However, the DDK in India [25] had extremely low SO_2 concentrations (0.0047 mg/m^3) owing to the use of biomass fuel and not coal. $PM_{2.5}$ emission concentrations in FCBTKs (303 ± 152 mg/m^3) in Nepal were higher than those in India or Bangladesh [18,25]. IDZKs (148 ± 61 mg/m^3) had comparable emissions with kilns measured in Bangladesh and Vietnam [17,26], but were higher than the VSBK kiln and lower than DDK kilns in India [25]. The highest concentrations observed in DDK kilns in India were due to the use of only twigs and leaves as fuel. Mass concentrations of BC emitted from all kilns measured in Nepal (55.5 ± 16.4 mg/m^3 for FCBTKs and 21.7 ± 15.5 mg/m^3 for IDZKs) were observed to be in an intermediary range compared with earlier studies. Few kilns in India exhibited higher BC, while some in Bangladesh indicated lower BC emissions. However, to better understand the emission pattern, we need to estimate emission factors (EFs) of different pollutants based on per kilogram of fuel used and per kilogram of brick produced.

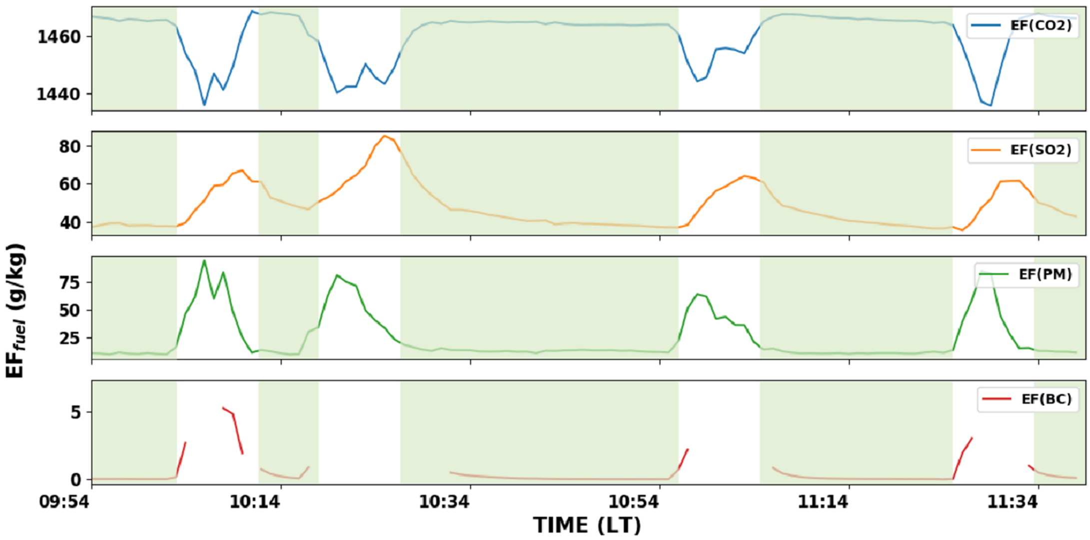

Figure 4. Real-time temporal profile of fuel-based emission factors (g/kg) of gaseous and particulate pollutants at FCBTK1, depicted for four combustion cycles where light green patch denotes non-feeding cycles and white patch denotes feeding cycles.

Table 2. Stack gaseous and particulate pollutants concentration at 25 °C and 1 atm pressure.

Pollutants	CO_2	SO_2	$PM_{2.5}$	BC
Kiln	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}
FCBTK 1	48,104 ± 12,101	1636 ± 791	522 ± 63	63 ± 150
FCBTK 2	48,756 ± 18,541	1012 ± 1103	245 ± 15	51 ± 74
FCBTK 3	36,038 ± 22,626	198 ± 420	171 ± 30	35 ± 79
FCBTK 4	51,800 ± 20,022	94 ± 86	274 ± 40	73 ± 76
Average	**46,175 ± 6947**	**735 ± 728**	**303 ± 152**	**55.5 ± 16.4**
IDZK 1	31,803 ± 8711	717 ± 237	207 ± 41	39 ± 30
IDZK 2	37,235 ± 19,981	192 ± 74	85 ± 8	9 ± 13
IDZK 3	37,878 ± 15,714	205 ± 80	152 ± 25	17 ± 20
Average	**35,639 ± 3337**	**371 ± 299**	**148 ± 61**	**21.7 ± 15.5**

Table 3. Summary of emission concentrations (mg/m³) of different pollutants in normal conditions (25 °C, 1 atm pressure) in this study, compared to previous studies.

Kin Type	Country	Study Year	Kilns	*n*	Fuels	CO_2	SO_2	$PM_{2.5}$	BC	References
Traditional	Nepal	2017	FCBTKs	4	Coal, rice husk, briquette	46175	735	303	55.5	Present study
	India	2011	FCBTKs	3	Coal, tires, wood logs	35500	321	94	80.0	[25]
	Bangladesh	2017–2018	FCBTKs	10	Coal and biomass	5254	578	141	16.6	[18]
	Vietnam	2007	Traditional-improved	2	Coal	-	81	114	-	[27]
Improved	Nepal	2017	IDZKs	3	Coal, rice husk, sawdust	35639	371	148	21.7	Present study
	Bangladesh	2017–2018	IDZKs	6	Coal	6995	332	128	11.8	[18]
			Hoffman	2	Coal	2350	316	109	8.9	
	India	2011	IDZKs	2	Coal	36500	143	-	19.0	[25]
			DDK	1	*Eucalyptus* twigs and leaves	86500	0.0047	331	98.0	
			VSBKs	2	Coal	-	522	71	1.2	
	South Africa	2018	Model kiln	13	Coal	9220	29	-	-	[26]

6.2. Fuel-Based Emission Factors (EF_{fuel})

The fuel-based emission factor calculation depends upon a number of factors, starting from the kiln technology, maintenance of the kilns, the fuel/fuel mixture used for firing the bricks to the size of the kiln but not only limited to these. From Table 1, it can be observed that the number of bricks produced in different kilns vary from each other, and the fuel/fuel mixture used also varies largely from kiln to kiln, which can introduce changes in the carbon content, gross calorific value, and specific energy consumption. Hence, variabilities in all the above mentioned factors can easily introduce a certain amount of variability in the emission estimates. However, in order to overcome these challenges and increase the precision of measurements, we have to increase the number of kiln measurements, which can be a considered as a further scope of the study.

6.2.1. Fuel-Based CO_2 Emission Factor

The average EF_{fuel} of CO_2 for FCBTKs and IDZKs is estimated to be 1633 ± 134 g/kg and 1981 ± 232 g/kg, respectively; this has been represented as box plots (Figure 5, Table 4). Complete combustion of carbon produces only CO_2 and water; incomplete combustion produces CO_2, water, CO, soot, and other trace gases. In the IDZKs, a better air–fuel mixture and turbulence due to the zigzag course of the fire enhances airflow inside the stacked bricks, and this may account for efficient burning. Apart from this, the type of fuel used (carbon content of fuel) also influences the EF. In most of the FCBTKs, the carbon content of the fuel ranged between 40% and 50% (mean 45%) and the EF_{fuel} for CO_2 ranged between 1466 ± 5 and 1793 ± 53. However, in the case of IDZK kilns, the carbon content of the fuel ranged between 45% and 60% (mean 55%) and the EF_{fuel} for CO_2 lay between 1715 ± 8 and 2135 ± 6. The reason for variation in the carbon content of the fuel was the large variability in the fuel mixtures used for firing the bricks. As suggested in Table 1, in two of the IDZKs, the fuel used was purely coal, and they also had the highest EF_{fuel} for CO_2. However, in all four FCBTKs and the remaining IDZK3, a mixture of coal with rice husk, sawdust, or bagasse was used in different proportions. This resulted in a lowering of the carbon content of the fuel used. In general, coal has a higher carbon content value than other biomass fuels such as rice husk, sawdust, and briquettes. Hence, kilns using a higher proportion of coal emitted more CO_2 in comparison to those using a mixture of coal and biomass fuels. It was also evident from the large variability of EF_{fuel} of CO_2 of IDZ1, 2 (2093, 2135 g/kg) compared with IDZ3 (1715 g/kg), where kiln design were the same, but the fuels used were different. Overall, the better design of IDZKs also allowed for better combustion, promoting higher EF_{fuel} for CO_2 in comparison to the FCBTKs.

EF_{fuel} for CO_2 among the traditional kilns, as observed in past literature, varied from 1526 g/kg to 2182 g/kg (Table 5). The average EF_{fuel} for CO_2 (1633 g/kg) in the FCBTKs measured lay in a range of values comparable with those observed in previous studies, except for traditional kilns from Mexico [13]. However, the FCBTK1 measured in the present study used a mixture of coal and sawdust, and its EFs were observed to be lower than the kiln in Mexico. Hypothetically, kilns using only biomass fuel were supposed to have the lowest EF_{fuel} for CO_2, as in the case of the Mexican kiln [13]. The lower carbon content (40.68%) of the fuel mixture used in FCBTK1 than the fuel mixture used in the Mexican kilns (43.43%) [13] may, therefore, justify the lower EF_{fuel} CO_2 of FCBTK1.

The difference in the EF of IDZKs measured in this study, in comparison to those observed during the NAMaSTE campaign, may be due to changes in fuel carbon content resulting from changes in fuel mixture. This is justifiable by the respective carbon content of fuels (55% on average for IDZKs in our study and 72.21% for the IDZK in the NAMaSTE campaign).

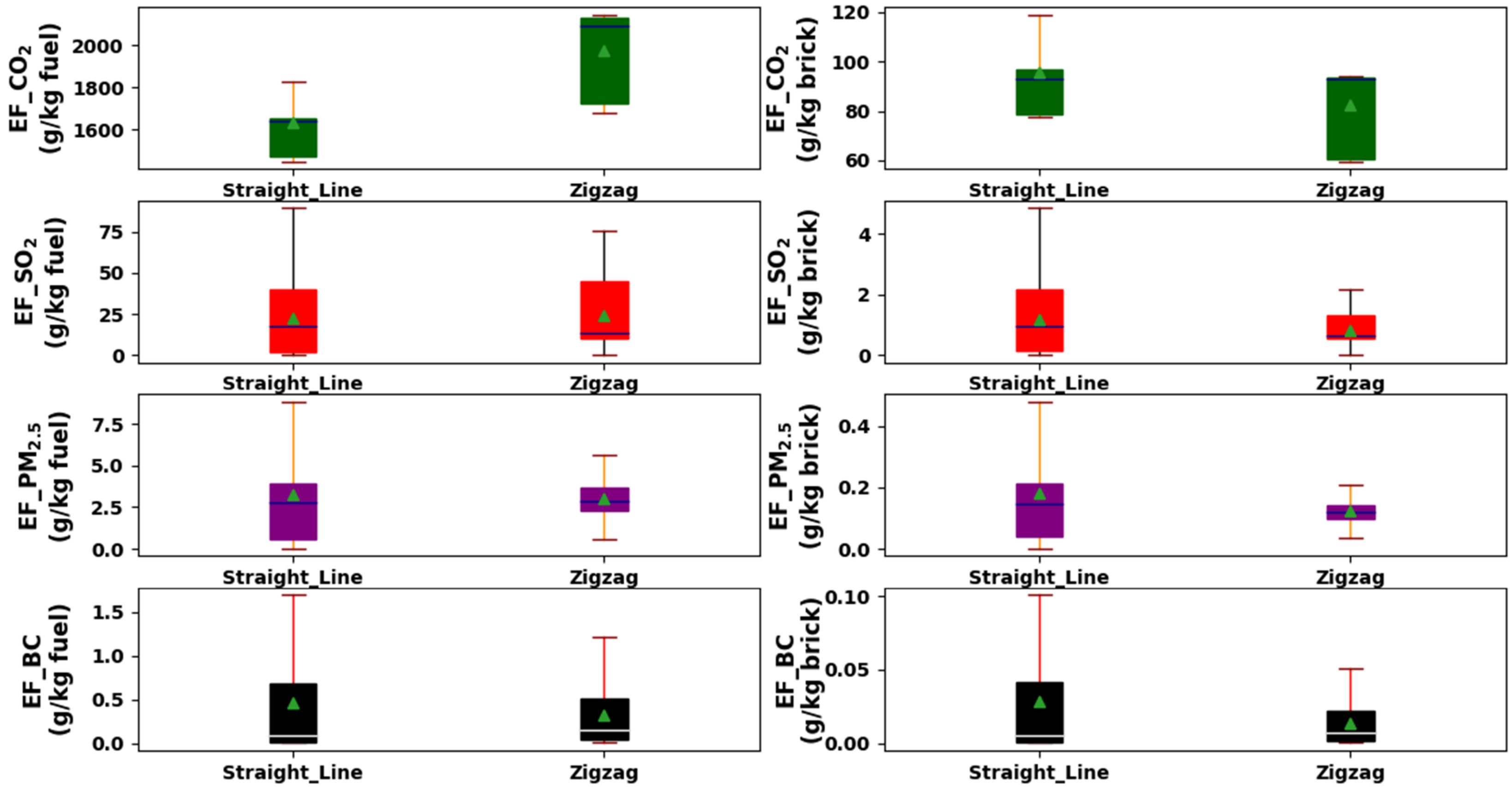

Figure 5. Box-and-whisker plots of the average of fuel-based (g/kg) and production-based (g/kg brick) emission factors of gaseous and particulate pollutants for straight-line and zigzag kilns. The boxes in the box-and-whisker plot extend from the Q1 to the Q3 quartile values of the data, having the difference between Q3 and Q1 as interquartile range (IQR), with a horizontal line at the median (Q2) and a triangle showing the mean value of the data. The position of the whiskers is set to 1.5 × IQR (IQR = Q3 − Q1) from the edges of the box where the green, orange, purple, and black box represent emission factors of CO_2, SO_2, $PM_{2.5}$, and BC, respectively.

Table 4. Average EF_{fuel} (g/kg) with standard deviations along with its minimum and maximum value for different pollutants in all the measured kilns. CO_2 values have been rounded off to the nearest whole number.

Pollutants	CO_2			SO_2			$PM_{2.5}$			BC		
Kiln	EF_{fuel}	**Min**	**Max**	EF_{fuel}	**Min**	**Max**	EF_{fuel}	**Min**	**Max**	EF_{fuel}	**Min**	**Max**
FCBTK 1	1466 ± 5	1447	1472	49 ± 12	4.8	87.6	7.4 ± 6.7	2.4	29.0	0.7 ± 1.5	0.002	7.1
FCBTK 2	1793 ± 53	1527	1826	32 ± 23	15.3	315	3.6 ± 2.5	1.1	15.3	0.5 ± 0.8	0.01	2.8
FCBTK 3	1630 ± 14	1566	1646	5 ± 7	0.6	32.3	1.3 ± 2.0	0.1	9.0	0.4 ± 0.7	0.00004	2.3
FCBTK 4	1641 ± 9	1616	1652	3 ± 2	0.4	17.2	3.1 ± 3.4	0.02	31.8	0.7 ± 0.7	0.002	3.9
Average	**1633 ± 134**			**22 ± 22**			**3.8 ± 2.6**			**0.6 ± 0.2**		
IDZK 1	2093 ± 11	2064	2120	49 ± 10	2.5	75.5	4.0 ± 0.8	2.1	9.3	0.6 ± 0.5	0.021	2.0
IDZK 2	2135 ± 6	2109	2147	13 ± 4	0.01	20.5	2.5 ± 0.6	1.4	5.1	0.3 ± 0.4	0.01	2.0
IDZK 3	1715 ± 8	1677	1727	10 ± 7	2.5	107.6	2.9 ± 2.5	0.5	36.4	0.3 ± 0.3	0.002	1.3
Average	**1981 ± 232**			**24 ± 22**			**3.1 ± 1**			**0.4 ± 0.2**		

Table 5. Summary of fuel-based emission factors (g/kg of fuel) of different pollutants in this study compared to previous studies.

Kiln Type	**Country**	**Study Year**	**Kilns**	***n***	**Fuels**	CO_2	SO_2	$PM_{2.5}$	**BC**	**References**
Traditional	Nepal	2017	FCBTKs	4	Coal, rice husk, briquette	1633	22	3.8	0.6	Present study
	Nepal	2015	Clamp Kiln	1	Coal, hardwood	2102	13	10.7	0.02	[14,15]
	India	2011	FCBTKs	3	Coal, tires, wood logs	2182	10.5	3.03	2.4	[25]
	India	2011–2012	FCBTKs	3	Coal and wood	-	-	1.7–4.4	1.8–3.7	[17]
	India	2015	FCBTKs	10	Coal	-	13.03	19.8	-	[28]
	Bangladesh	2017–2018	FCBTKs	10	Coal and biomass	-	26.7	6.1	0.4	[18]
	Mexico	2007	Batch-Style	2	Biofuel including crop waste	1736–1787	-	1.2–2.0	0.6–1.5	[29]
	Mexico	2013	Traditional-Fixed	1	Sawdust, wood, diesel	1668	0.1	1.3	0.5	[13]
	Mexico	2013	Traditional-Campaign	1	Biomass	1526	0.3	4.6	0.3	[13]
Improved	Nepal	2017	IDZKs	3	Coal, rice husk, sawdust	1981	24	3.1	0.4	Present study
	Nepal	2015	IDZK	1	Coal and bagasse	2620	12.7	15.1	0.1	[14,15]
	Bangladesh	2017–2018	IDZKs	6	Coal	-	18.5	5.9	0.3	[18]
	Bangladesh	2017–2018	Hoffman	2	Coal	-	33.7	4.7	0.3	[18]
	India	2011	IDZKs	2	Coal	2017	3.9	2.7	0.8	[25]
	India	2011–2012	IDZKs	3	Coal	-	-	0.60–1.20	0.07–0.5	[17]
	India	2011–2012	VSBK	1	Coal	-	-	1.3	0.1	[17]
	India	2011–2012	DDK	1	Wood		-	3	1.1	[17]
	Vietnam	2011–2012	TK	1	Coal	-	-	1.6	0.01	[17]
	Vietnam	2011–2012	VSBK	1	Coal	-	-	1.3	0.01	[17]
	Mexico	2013	MK2	1	Biomass	1582	1	1.9	0.2	[13]
	China	2013	Hoffman	18	Coal	1940	2.2	0.6	0.002	[30]
	China	2014	Hoffman	10	Coal	1920	2	2.7	0.06	[30]

6.2.2. Fuel-Based SO_2 Emission Factor

The EF_{fuel} of SO_2 for FCBTK and IDZKs varied between 3 ± 2 and 49 ± 12 g/kg, and average values were 22 ± 22 g/kg and 24 ± 22 g/kg, respectively (Figure 5, Table 4). The average sulfur content of the fuel used in FCBTKs and IDZKs was 2.04% and 3.05%, respectively, although variability existed between individual kilns depending upon the changes in fuel types. This indicated that SO_2 emissions did not vary strongly with the change in kiln design; rather, it depended on the sulfur content of the fuel/fuel mixture used. In general, the sulfur content of coal was observed to be higher in comparison to that of biomass. Kilns using only coal, therefore, were expected to have a higher EF_{fuel} for SO_2. However, considerable variability was observed, due to differences in the fuel mixtures used and fuel feeding processes.

Among the FCBTKs, the EF_{fuel} of SO_2 was observed to be highest in FCBTK1 (49 ± 12), and this was also corroborated by the highest sulfur content (4.6%) of the fuel mixture. As expected, the EF_{fuel} of SO_2 in FCBTK3 should have been the lowest as it used briquettes (normally made of bagasse) as the only fuel. However, the lowest EF_{fuel} of SO_2 was observed for FCBTK4 (using coal and rice husk). This indicated that the mixture of certain additives in briquette production led to slightly higher EF_{fuel} for SO_2. IDZK1 and IDZK2 kilns used coal as the only fuel, while IDZK3 used a mixture of coal, rice husk, and sawdust. The fuel-based emission factor for IDZK3 was also the lowest, as expected, owing to the change in fuel mixture. In kiln IDZK1, the EF_{fuel} of SO_2 was also observed to be higher than in IDZK2 and IDZK3, and was comparable to that of FCBTK1. This indicated that the sulfur content of the fuel may be an indicator of EF estimates, but some uncertainties still need to be resolved. This challenge may be related to the method of firing or any other kiln maintenance issues. Although real-time concentrations are also used for SO_2 emission estimates, they are also dependent on the concentrations of CO and CO_2. Thus, higher concentrations of SO_2 in kiln IDZK1, along with higher emission estimates for CO and CO_2 for this kiln, produced higher EF_{fuel} of SO_2 overall.

Average EF_{fuel} for SO_2 in FCBTKs and IDZKs in this study was slightly higher than that estimated in other studies, except in Bangladesh [18] (Table 5). For Bangladesh, higher coal sulfur content could be attributed to the higher EF [18]. This may also be the case for kilns in Nepal when compared to those of India, Mexico, Vietnam, or China. However, use of biomass fuels, such as wood and sawdust in the Mexican kilns (MK2, traditional-fixed, and traditional-campaign kiln type) contributed significantly to the reduction in EF_{fuel} of SO_2.

6.2.3. Fuel-Based $PM_{2.5}$ Emission Factors

The average EF_{fuel} of $PM_{2.5}$ for FCBTKs and IDZKs was estimated to be 3.8 ± 2.6 g/kg and 3.1 ± 1 g/kg, respectively (Figure 5, Table 4).

Intercomparison of the FCBTKs in the present study indicated large variability in EF_{fuel} of $PM_{2.5}$, ranging from 1.3 to 7.4 g/kg. This might be attributed to the individual kiln characteristics (age and maintenance) and changes in fuel mixture. In the present study, FCBTK1 was observed to have the highest EF_{fuel} of $PM_{2.5}$ and it was also the oldest kiln measured. The higher fuel-based emission factor was also supported by the higher concentrations of $PM_{2.5}$ emitted from this particular kiln. Further, a fuel mixture of rice husk and coal was used in FCBTK1, as well as in FCBTK4, but FCBTK4 had an EF_{fuel} of $PM_{2.5}$ comparable to FCBTK2 or 3. This indicated that changes in the ratio of fuel mixture or brick stacking pattern in the chambers, along with overall maintenance of the kiln, could also influence the EF_{fuel} of $PM_{2.5}$. Among the IDZKs, the variation in EF_{fuel} of $PM_{2.5}$ ranged between 2.5 and 4.0 g/kg, indicating a comparable EF estimate. However, a change in fuel mixture from pure coal to a mixture of coal and rice husk in different proportions in IDZK3 did not influence a significant change in $\mathrm{EF_{fuel}}$ of $PM_{2.5}$. This indicated that, overall, the zigzag arrangement and proper firing will definitely reduce particulate pollution.

Past literature indicated the average EF_{fuel} of $PM_{2.5}$ for traditional kilns lies between 1.2 g/kg and 19.8 g/kg (Table 5); and that for the IDZKs lies between 0.6 g/kg and 15.1 g/kg (Table 5).

The unexpectedly higher EFs for improved kilns came from the IDZK measured in one of the studies undertaken in Nepal during the NAMaSTE campaign (prior to our study). The study estimated EF_{fuel} of $PM_{2.5}$ for only one IDZK (15.1 g/kg) and one clamp kiln (traditional type; 10.7 g/kg). The higher EF_{fuel} of $PM_{2.5}$ observed in the IDZK was attributed to the increased emissions of sulfate (likely in the form of sulfuric acid) and hygroscopic water. Overall, the comparison of different brick kilns operational in the Asian region with those in Mexico indicated comparable EF_{fuel} of $PM_{2.5}$ for traditional and improved brick kilns, excluding the measurements made during the NAMaSTE campaign. The slight changes observed in different regions can be attributed to the changes in fuel quality, fuel mixture, and mix ratio, along with the feeding processes. The instruments used for measurement in different regions might also have introduced a certain amount of bias: taking this into account was beyond the scope of the present study. The results indicate that improved design will definitely result in emission reductions, but the magnitude depends on how efficiently brick stacking and firing is performed.

6.2.4. Fuel-Based BC Emission Factors

EF_{fuel} of BC for FCBTKs (0.6 ± 0.2 g/kg) was approximately 35% higher than that of IDZKs (0.4 ± 0.2 g/kg) measured in the present study (Figure 5, Table 4). Conditions responsible for variability in emissions of $PM_{2.5}$ also led to changes in BC emissions. A visible change in the fume quality of the IDZKs (white fume) in comparison to that of FCBTKs (black fumes) was also observed with respect to the reduction in emissions of BC from the kiln chimneys.

In a previous study by Weyant et al. [17], EF_{fuel} of EC in different South Asian brick kilns (the majority in India and two in Vietnam) was estimated to be broadly in the range of 0.01–3.7 g/kg. Average EF_{fuel} of BC for FCBTKs, IDZKs, and a Hoffman kiln measured in Bangladesh were 0.4 ± 0.2, 0.3 ± 0.1, and 0.3 ± 0.1 g/kg, respectively. The EF_{fuel} of BC in-stack flue gases of Hoffman kilns in China was estimated to be 0.029 g/kg [30]. A recent study conducted in Nepal during the NAMaSTE campaign indicated EF_{fuel} of BC for 0.1 g/kg in an IDZK, and 0.02 g/kg in a clamp kiln [14]. The results of the present study indicated EF_{fuel} of BC for FCBTKs were comparable to the values observed in previous studies [14,15,17,18,25]. The mean EF in IDZKs were comparable to those of the EF for Hoffman kilns in Bangladesh and previous studies in Nepal (Table 5). At the same time, a more improved kiln design (Hoffman kiln), operational in China and Bangladesh, had comparable emissions to those of the IDZKs, indicating similarities in BC reduction. Overall, the study sufficiently highlighted the reduction in EF by a redesign that changed traditionally operated FCBTKs into IDZKs. However, considerable care must be taken in efficient stacking and firing of bricks to attain the best results.

6.3. Production-Based Emission Factors of CO_2, SO_2, $PM_{2.5}$, and BC

The mass production-based emission factors ($EF_{kgbrick}$) for individual kilns and all four pollutants have been presented in Table 6. The average ($EF_{kgbrick}$) of CO_2 for FCBTKs and IDZKs were estimated to be 96 ± 16 g/kg and 82 ± 19 g/kg of fired brick, respectively. The same for SO_2 in FCBTKs and IDZKs were estimated to be 1.2 ± 1.2 g/kg and 0.9 ± 0.5 g/kg, respectively. Mean $EF_{kgbrick}$ of $PM_{2.5}$ and BC for FCBTKs and IDZKs were estimated to be 0.2 ± 0.1, 0.1 ± 0.0 g/kg and 0.03 ± 0.01, 0.01 ± 0.00 g/kg respectively (Table 6). The intervariability between individual FCBTK and IDZKs may be due to the changes in EF_{fuel}, specific energy consumption (SEC), weight of fired brick (Wb), and gross caloric value (GCV). Hence, variation in any of the parameters can introduce variations in the $EF_{kgbrick}$. Even kilns of similar technology do not necessarily guarantee similar SEC, Wb, and GCV, as these parameters differs largely from kiln to kiln, based on the fuel used, fuel feeding pattern, etc. (Table 1). However, the difference between the two different types of kilns was significant compared to the differences between the individual kilns. Comparison of the $EF_{kgbrick}$ indicated slightly lower quantities of CO_2 per kilogram of brick in Nepal than in other reported countries, while that for SO_2, $PM_{2.5}$, and BC in Nepal were comparable to other countries shown in Table 7 [8,17,18,25].

Table 6. Average $EF_{kgbrick}$ (g/kg brick) with standard deviations along with its minimum and maximum value for different pollutants in all the measured kilns. CO_2 values have been rounded off to the nearest whole number.

Pollutants	**CO_2**			**SO_2**			**$PM_{2.5}$**			**BC**		
Kiln	**$EF_{kgbrick}$**	**Min**	**Max**	**$EF_{kgbrick}$**	**Min**	**Max**	**$EF_{kgbrick}$**	**Min**	**Max**	**$EF_{kgbrick}$**	**Min**	**Max**
FCBTK 1	79 ± 0.3	77.5	78.9	2.6 ± 0.6	0.3	4.7	0.4 ± 0.3	0.1	1.6	0.04 ± 0.08	0.0001	0.4
FCBTK 2	91 ± 2.7	77.6	92.8	1.6 ± 1.2	0.8	16.0	0.2 ± 0.1	0.06	0.8	0.03 ± 0.04	0.001	0.1
FCBTK 3	118 ± 1.0	113.2	119.0	0.4 ± 0.5	0.04	2.3	0.1 ± 0.2	0.01	0.6	0.03 ± 0.05	0.000002	0.2
FCBTK 4	96 ± 0.5	94.7	96.8	0.2 ± 0.1	0.03	1.0	0.2 ± 0.2	0.001	1.9	0.04 ± 0.04	0.0001	0.23
Average	**96 ± 16**			**1.2 ±1. 2**			**0.2 ± 0.1**			**0.03 ± 0.01**		
IDZK 1	60 ± 0.3	59.6	61.2	1.4 ± 0.3	0.1	2.2	0.1 ± 0.02	0.06	0.3	0.02 ± 0.01	0.001	0.1
IDZK 2	94 ± 0.3	92.4	94.1	0.6 ± 0.2	0.0005	1.0	0.1 ± 0.03	0.1	0.2	0.01 ± 0.02	0.001	0.1
IDZK 3	93 ± 0.5	91.1	93.9	0.6 ± 0.4	0.1	5.8	0.2 ± 0.1	0.03	2.0	0.01 ± 0.01	0.0001	0.1
Average	**82 ± 19**			**0.9 ± 0.5**			**0.1 ± 0.0**			**0.01 ± 0.00**		

Table 7. Summary of emission factors of different pollutants per kilogram of brick produced (g/kg of fired brick) in this study compared to previous studies.

Kiln Type	**Country**	**Study Year**	**Kilns**	***n***	**Fuels**	**CO_2**	**SO_2**	**$PM_{2.5}$**	**BC**	**References**
Traditional	Nepal	2017	FCBTKs	4	Coal, rice husk, briquette	96	1.2	0.2	0.03	Present study
	India	2011	FCBTKs	3	Coal, tires, wood logs	115	0.7	0.2	0.1	[25]
		2011–2012	FCBTKs	3	Coal and wood	-	-	0.08–0.3	0.09–0.3	[17]
		2011	FCBTKs	5	Coal and others	179	0.5	0.9	-	[8]
	Bangladesh	2017–2018	FCBTKs	10	Coal and biomass	-	1.8	0.4	0.03	[18]
	Bangladesh	2010	FCBTKs	-	Coal and biomass	173	1.5	2.3	0.9	[31]
	Vietnam	2007	Traditional-improved	2	Coal	-	1.5	0.5	-	[27]
Improved	Nepal	2017	IDZKs	3	Coal, rice husk, sawdust	82	0.9	0.1	0.01	Present study
	Bangladesh	2017–2018	IDZKs	6	Coal	-	1.1	0.4	0.02	[18]
		2017–2018	Hoffman	2	Coal	-	1.8	0.3	0.01	
	India	2011	IDZKs	2	Coal	103	0.3	0.1	0.04	[25]
		2011	IDZKs	3	Coal	96	0.2	0.2	-	[8]
		2011	VSBK	1	Coal	118	0.1	0.1	-	
		2011–2012	IDZKs	3	Coal	-	-	0.03–0.05	0.02–0.004	[17]
		2011–2012	VSBK	1	Coal	-	-	0.05	0.002	
		2011–2012	DDK	1	Wood		-	0.5	0.2	
	Vietnam	2011–2012	TK	1	Coal	-	-	0.2	0.001	
		2011–2012	VSBK	1	Coal	-	-	0.1	0.001	

7. Conclusions

This study provides EF estimates for two of the most prevalent types of brick kilns in Nepal. General characteristics of the kiln indicate that brick production capacity was observed to be higher in IDZKs than in FCBTKs, while the mean brick weight was observed to be slightly higher in FCBTKs than in IDZKs. Compared with IDZKs, FCBTKs had lower CO_2, comparable SO_2 and higher $PM_{2.5}$ and BC based on EFs from 1 kg of fuel/fuel mixture used in the kilns. However, EF per kilogram of manufactured brick clearly indicate lower emission estimates for all pollutants measured during the study. Hence, converting the technology from straight-line kilns to zigzag kilns can reduce the emissions of $PM_{2.5}$ and BC. The magnitude of reduction would vary based on EF estimates of per kilogram fuel or per kilogram weight of brick. The EF per kilogram fuel suggests a reduction in $PM_{2.5}$ by ~20% and BC by ~30%, while emission reductions with respect to per kilogram weight of fired brick were approximately 40% for $PM_{2.5}$ and 55% for BC. Based on these estimates, converting kilns from straight-line to zigzag design can play a significant role in reducing emissions, and will promote cleaner and more efficient brick-making technology.

However, there is still a scope for measuring a greater number of kilns spread across different geographical conditions of Nepal, in order to better understand the overall emission scenario. Detailed chemical characterization of the emissions from brick kilns could add to the existing knowledge database. Expanding the emission measurement strategy to other parts of the region (Pakistan, where any such measurements are largely missing) would also provide a broader overview of EF estimates of brick kilns in South Asia. A detailed energy performance analysis of the brick kilns could also aid in better understanding of the interplay between emissions and the energy budget. Overall, such studies would also assist in upgrading the existing regional and global emission inventories, which lack local estimates and aid in better atmospheric modeling.

Author Contributions: The study was designed by S.P.P., B.B.P., S.S., S.A., K.L.S. Field work was conducted by S.A., S.S., S.N., P.S. Data analysis performed by S.P.P., B.B.P., S.S., S.A., K.L.S., S.N., P.S., P.S.M. The first draft of the paper was written by S.N., P.S.M., S.P.P. and finally edited and approved by all co-authors.

Acknowledgments: This work was partially supported by core funds of ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland and United Kingdom. Our sincere thanks to Ashish Rai and Amit Chaudhary for providing energy measurement data. Special thanks to Subash Bhattarai and Vikrant Sapkota for assistance with writing codes, Anushilan Acharya for assistance with plotting the map. We would like to acknowledge Federation of Nepal Brick Industries (FNBI) and the kiln owners for allowing us to conduct the study.

Conflicts of Interest: The authors declare that they have no actual or potential competing financial interests.

References

1. Kim, B.M.; Park, J.-S.; Kim, S.-W.; Kim, H.; Jeon, H.; Cho, C.; Kim, J.-H.; Hong, S.; Rupakheti, M.; Panday, A.K.; et al. Source apportionment of PM10 mass and particulate carbon in the Kathmandu Valley, Nepal. *Atmos. Environ.* **2015**, *123*, 190–199. [CrossRef]
2. Schmidt, C.W. Modernizing Artisanal Brick Kilns: A Global Need. *Environ. Health Perspect.* **2013**, *121*, 242–249. [CrossRef] [PubMed]
3. Mues, A.; Lauer, A.; Lupascu, A.; Rupakheti, M.; Kuik, F.; Lawrence, M.G. WRF and WRF-Chem v3.5.1 simulations of meteorology and black carbon concentrations in the Kathmandu Valley. *Geosci. Model Dev.* **2018**, *11*, 2067–2091. [CrossRef]
4. Zhong, M.; Saikawa, E.; Avramov, A.; Chen, C.; Sun, B.; Ye, W.; Keene, W.C.; Yokelson, R.J.; Jayarathne, T.; Stone, E.A.; et al. Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE): Emissions of particulate matter and sulfur dioxide from vehicles and brick kilns and their impacts on air quality in the Kathmandu Valley, Nepal. *Atmos. Chem. Phys. Discuss.* **2018**, 1–34. [CrossRef]
5. Shaikh, S.; Nafees, A.A.; Khetpal, V.; Jamali, A.A.; Arain, A.M.; Yousuf, A. Respiratory symptoms and illnesses among brick kiln workers: A cross sectional study from rural districts of Pakistan. *BMC Public Health* **2012**, *12*, 999. [CrossRef] [PubMed]

6. Manandhar, U.M.; Dangol, S.B. *Study on Evaluating Energy Conservation Potential of Brick Production in SAARC Countries*; A Report on Nepal; SAARC Energy Centre: Islamabad, Pakistan, 2013.
7. Brick Sector in Nepal National Policy Framework Prepared by MinErgy in Collaboration. 2017. Available online: http://www.ccacoalition.org/en/resources/brick-sector-nepal-national-policy-framework (accessed on 21 December 2018).
8. Rajarathnam, U.; Athalye, V.; Ragavan, S.; Maithel, S.; Lalchandani, D.; Kumar, S.; Baum, E.; Weyant, C.; Bond, T. Assessment of air pollutant emissions from brick kilns. *Atmos. Environ.* **2014**, *98*, 549–553. [CrossRef]
9. Asian Development Bank. *Nepal Energy Sector Assessment, Strategy, and Roadmap*; Asian Development Bank: Manila, Philippines, 2017; Volume 17.
10. Sarkar, C.; Sinha, V.; Sinha, B.; Panday, A.K.; Rupakheti, M.; Lawrence, M.G. Source apportionment of NMVOCs in the Kathmandu Valley during the SusKat-ABC international field campaign using positive matrix factorization. *Atmos. Chem. Phys.* **2017**, *17*, 8129–8156. [CrossRef]
11. Lopez, A.; Lyoda, N.; Segal, R.; Tsai, T. Evaluating the Brick Industry in South Asia. 2012. Available online: https://rmi.org/wp-content/uploads/2017/04/Pathways-to-Efficiency-in-the-South-Asia-Brickmaking-Industry-Carbon-War-Room_0.pdf (accessed on 21 December 2018).
12. Maharjan, S.; Technology Research and Development Centre, Federation of Nepal Brick Industries, Kathmandu, Nepal. Personal communication, 2017.
13. Zavala, M.; Molina, L.T.; Maiz, P.; Monsivais, I.; Chow, J.C.; Watson, J.G.; Munguia, J.L.; Cardenas, B.; Fortner, E.C.; Herndon, S.C.; et al. Black Carbon, Organic Carbon, and Co-Pollutants Emissions and Energy Efficiency from Artisanal Brick Production in Mexico. *Atmos. Chem. Phys. Discuss.* **2017**, 1–28. [CrossRef]
14. Stockwell, C.E.; Christian, T.J.; Goetz, J.D.; Jayarathne, T.; Bhave, P.V.; Praveen, P.S.; Adhikari, S.; Maharjan, R.; DeCarlo, P.F.; Stone, E.A.; et al. Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE): Emissions of trace gases and light-absorbing carbon from wood and dung cooking fires, garbage and crop residue burning, brick kilns, and other sources. *Atmos. Chem. Phys.* **2016**, *16*, 11043–11081. [CrossRef]
15. Jayarathne, T.; Stockwell, C.E.; Bhave, P.V.; Praveen, P.S.; Rathnayake, C.M.; Islam, M.R.; Panday, A.K.; Adhikari, S.; Maharjan, R.; Goetz, J.D.; et al. Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE): Emissions of particulate matter from wood- and dung-fueled cooking fires, garbage and crop residue burning, brick kilns, and other sources. *Atmos. Chem. Phys.* **2018**, *18*, 2259–2286. [CrossRef]
16. Panday, A.K.; Prinn, R.G. Diurnal cycle of air pollution in the Kathmandu Valley, Nepal: Observations. *J. Geophys. Res.* **2009**, *114*, D09305. [CrossRef]
17. Weyant, C.; Athalye, V.; Ragavan, S.; Rajarathnam, U.; Lalchandani, D.; Maithel, S.; Baum, E.; Bond, T.C. Emissions from South Asian Brick Production. *Environ. Sci. Technol.* **2014**, *48*, 6477–6483. [CrossRef] [PubMed]
18. Haque, M.I.; Nahar, K.; Kabir, M.H.; Salam, A. Particulate black carbon and gaseous emission from brick kilns in Greater Dhaka region, Bangladesh. *Air Qual. Atmos. Heal.* **2018**, 1–11. [CrossRef]
19. Thompson, R.; Weyant, C.; Bond, T.; Baum, E. *Brick Kiln Emissions Sampling Protocol:0 Dilution Sampling for Climate-Relevant Particle Emissions*; Climate & Clean Air Coalition: Paris, France, 2016; pp. 1–36. Available online: http://www.ccacoalition.org/sites/default/files/resources/Brick_Kiln_Emissions_Sampling_Procedure_v11.pdf (accessed on 21 December 2018).
20. Engineering, M.A. Ratnoze2 User Guide. 2016. Available online: http://www.mtnaireng.com/Ratnoze1_User_Guide_v8.pdf (accessed on 21 December 2018).
21. Adhikari, S.; Mahapatra, P.S.; Sapkota, V.; Puppala, S.P. Characterizing Emissions from Agricultural Diesel Pumps in the Terai Region of Nepal. *Atmosphere* **2019**, *10*, 56. [CrossRef]
22. Morvay, Z.K.; Gvozdenac, D.D. *Applied Industrial Energy and Environmental Management*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2008; ISBN 9780470697429.
23. Ismaila, A.; Abdullahi, I.; Garba, N.N. Investigation on bioass briquettes as energy source in relation to their calorific values and measurement of their total carbon and elemental contents for efficient biofuel utilization. *Appl. Sci. Res.* **2013**, *4*, 303–309.
24. Srinath, S.; Reddy, G.V. Combustion and Emission Characteristics of Rice husk in a Rectangular Fluidized Bed Combustor. In Proceedings of the 2nd International Conference on Environmental Science and Technology, Singapore, 26–28 Februagy 2011; Volume 6, pp. 343–346.

25. Maithel, S.; Lalchandani, D.; Malhotra, G.; Bhanware, P.; Rajarathnam, U.; Ragavan, S.; Athalye, V.; KR, B.; Reddy, S.; Bond, T.; et al. *Monitoring of Brick Kilns Strategies for Cleaner Brick Production in India*; Shakti Sustainable Energy Foundation: Delhi, India, 2012.
26. Akinshipe, O.; Kornelius, G. Quantification of atmospheric emissions and energy metrics from simulated clamp kiln technology in the clay brick industry. *Environ. Pollut.* **2018**, *236*, 580–590. [CrossRef] [PubMed]
27. Le, H.A.; Oanh, N.T.K. Integrated assessment of brick kiln emission impacts on air quality. *Environ. Monit. Assess.* **2010**, *171*, 381–394. [CrossRef] [PubMed]
28. Suresh, R.; Kumar, S.; Mahtta, R.; Sharma, S. Emission factors for continuous fixed chimney Bull Trench Brick Kiln (FCBTK) in India. *Int. J. Adv. Eng. Manag. Sci. Infogain Publ.* **2016**, *2*, 662–670. [CrossRef]
29. Christian, T.J.; Yokelson, R.J.; Cárdenas, B.; Molina, L.T.; Engling, G.; Hsu, S.C. Trace gas and particle emissions from domestic and industrial biofuel use and garbage burning in central Mexico. *Atmos. Chem. Phys.* **2010**, *10*, 565–584. [CrossRef]
30. Chen, Y.; Du, W.; Zhuo, S.; Liu, W.; Liu, Y.; Shen, G.; Wu, S.; Li, J.; Zhou, B.; Wang, G.; et al. Stack and fugitive emissions of major air pollutants from typical brick kilns in China. *Environ. Pollut.* **2017**, *224*, 421–429. [CrossRef] [PubMed]
31. Guttikunda, S.K.; Begum, B.A.; Wadud, Z. Particulate pollution from brick kiln clusters in the Greater Dhaka region, Bangladesh. *Air Qual. Atmos. Heal.* **2013**, *6*, 357–365. [CrossRef]