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Emission and Reduction of Air Pollutants from Charcoal-Making Process in the Vietnamese Mekong Delta

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Abstract: Charcoal is a fuelwood commonly used for domestic purposes on the household scale in Africa and Southeast Asia. Earnings from charcoal production contribute to the income of local inhabitants in rural areas. Unfortunately, airborne emissions from the traditional charcoal-making process affect both human health and the ambient environment. A series of studies were performed at a charcoal-making village in the Vietnamese Mekong Delta (VMD) to assess: (i) air pollutant emissions from the traditional charcoal-making process; (ii) the impacts on human well-being and the environment of traditional charcoal production; (iii) the loading of carbon dioxide from a charcoal-making kiln; and (iv) the efficiency in reducing contaminants of an air pollution-controlling method developed at a charcoal-making kiln. Study results revealed that the traditional charcoal-making method causes a substantial loss of carbon from fuelwood materials and emits the products of incomplete combustion. These contaminants negatively impact human well-being and the environment. Carbon dioxide and incomplete combustion substances emitted from the charcoal-making kiln are potential causes of the global warming phenomenon. The installation of an air pollution-controlling system at the charcoal-making kiln is recommended as an urgent solution before alternatives would be found to control the impacts of charcoal production.

Keywords: air pollutant emission; air pollution reduction; charcoal-making kiln; fuelwood

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1. Introduction

Charcoal is one of the most essential energy-producing biomass-based materials, utilized to a great extent in developing countries [1]. In the traditional charcoal-making countries, charcoal production not only creates jobs to increase the local laborers' incomes, but also contributes to the development of the social economy and maintains cultural characteristics [2,3]. Charcoal can be made from various types of wood, such as palm oil shell, bamboo, mangrove, melaleuca etc. Produced charcoals have different quality and productivity depending on the type of raw materials. Charcoal can also be produced by different methods and instruments such as furnaces, drum kilns or traditional burning kilns [4]. With these instruments, the initial materials (i.e., wood, solid waste, sludge . . .) undertake a complicated process and are finally converted into charcoal, generally termed the carbonization process. The process involves complex phenomena, occurs at a wide temperature range [5] and is divided into various temperature stages depending on the method; for example, less than 200 °C, from 200 °C to 280 °C, from 280 °C to 500 °C and over 500 °C [6]. Responding to each stage of the carbonization process, various substances are produced including charcoal, tar, pyroligneous acid and gases. Several results obtained from the experiments at the laboratory scale have revealed that the main products of the wood hydrolysis process have various compositions. From these products, in total, around 33% correspond to charcoal (80% fixed carbon), 35.5% to pyroligneous acid, 6.5% to insoluble tar and 25% correspond to non-condensable gases [6]. Compositions of the incomplete combustion emitted from the traditional charcoal-making process may affect human health and pollute the environment [7,8]. According to the newsletter of Tanzania Traditional Energy Development and Environment Organization (TaTEDO) cited by Msuya et al. [9], over one million tons of produced charcoal is responsible for 109,500 ha of forest loss in Tanzania every year. Here, the local charcoal-making kilns have a productivity of around 11–19% for non-improved kilns and 27–30% for improved kilns, respectively. However, most of the charcoal makers in Tanzania do not like to use improved kilns due to their high investment costs. They prefer to use the non-improved conventional earth kilns because of their simplicity and low investment costs. Unfortunately, when this type of kiln is used, a large volume of wood is converted into ash instead of charcoal. Charcoal production in Tanzania also contributes to climate change, reduces agricultural productivity, destroys the environment and causes biodiversity loss.

In the Vietnamese Mekong Delta (VMD), charcoal production by traditional baked clay brick kilns is widespread in many provinces, such as Soc Trang, Hau Giang, and Ben Tre. The charcoal production capacity of each kiln is estimated to be between 8 - 12 tons of charcoal per charcoaling time. Carbonization time requires from 20 to 30 days, depending on the raw materials and operating conditions. The raw materials are various types of wood, which are characterized by a high carbon composition, a suitable price, and they are easy to find. The popular charcoaling wood in the VMD is mangrove *Rhizophora*. Here, charcoal is produced with the traditional kiln and in the absence of modern techniques and controlling measures to reduce substances emitted during the carbonization process. The substances emitted from the charcoal kilns may negatively affect the environment. However, there are no studies on the impact of the carbonization process in the VMD. Therefore, this study is to assess the carbonization process and its pollutant emissions. In addition, a measure is preliminarily performed to reduce the pollutants emitted during the carbonization process.

2. Materials and Methods

2.1. Study Site

The study was conducted at a charcoal-making village in Phu Tan Commune, Chau Thanh District, Hau Giang Province (Figure 1). Charcoal-making activity has gradually increased since 2013 due to charcoal demand for domestic consumption and exporting. Currently, the total number of charcoal kilns at the study site was 525 kilns and the charcoal production in 2016 was up to 70,593 tons/year, all without air pollutant-controlling systems (according to the author's survey). Charcoal making was the main livelihood of about 16% of the total households living here. The assessment of air pollutant emission from a charcoal kiln was carried out from December 2017 to June 2018, and then an investigation into the efficiency of air pollutant reduction was performed from October 2019 to April 2020.

2.2. Household Interviews

With the aim of having a comprehensive understanding for the impact of charcoal-making activity, household interviews were performed in the study site. A number of target households were randomly selected to interview based on Slovin's formula as follows:

$$n = \frac{N}{1 + N * e^2} \quad (1)$$

where:

n: the sample size of households selected for the interviews;
N: the total given households making charcoal in the study site (N = 227 households);
e: margin of error (e = 10%). Given the calculation result from Formula (1), which shows the sample size of 70 target households making charcoal.

To assess the impact of charcoal-making activity, 70 households that do not make charcoal were also randomly selected in the study site. A sample of the questionnaire is shown in Appendix A. Information recorded from the interviews focused on the local inhabitants' income, and the impacts of charcoal-making activities on human health and the ambient environment.

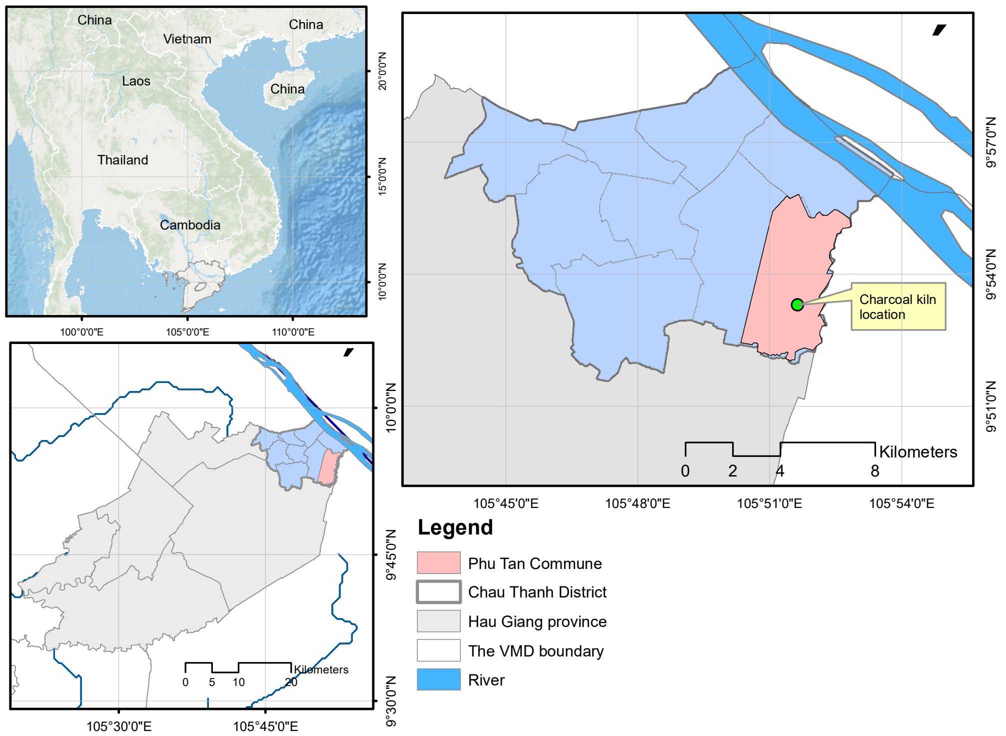


Figure 1. The location of the charcoal-making village.

2.3. *Determining the Concentration of Pollutants Emitted from the Carbonization Process*

Air pollution from the carbonization process was assessed by determining the concentration of the air quality parameters, including CO, CO_2, NO_2, SO_2 and particulate matter $PM_{2.5}$. The concentrations of CO, CO_2, NO_2, and SO_2 emitted from a charcoal kiln were measured at 6 periods of sampling, consisting of day 1, 5, 10, 15, 20, and 25, over a 25-day duration of a carbonization process. The sampling location was located at a fume exhausting hollow of the charcoal kiln. These parameters were directly measured in situ using a Kane 9106 Quintox combustion gas analyzer. Particulate matter $PM_{2.5}$ in the fume exhausted from the charcoal kiln was determined by an air quality detector, AirVisual Node. Concentrations of particulate matter $PM_{2.5}$ were determined at the charcoal kiln and locations at distances of 10, 50, 100, 200, 300, 1200, and 1500 m towards the main wind direction.

The mass of CO and CO_2 were determined by an experiment which was conducted with four specimens of two types of wood, *Rhizophora* and *Eucalyptus*, at two various stages: 25-year and 10-year *Rhizophora* (marked R25 and R10, respectively) and 10-year and 5-year *Eucalyptus* (marked E10 and E5, respectively). These specimens were dried at 105 °C to constant weight, and then the dry biomass of the specimens was calculated. Water vapor loss from each specimen of wood was identified according to the difference between fresh biomass and dry biomass. The main composition of all common types of wood is carbon, hydroxyl and oxygen, general formula $(CH_2O)_x$. Based on the determined water vapor, the mass of CO and CO_2 emitted from the specimens was calculated corresponding to the incomplete combustion Equation (2):

$$3CH_2O + 2O_2 \rightarrow CO_2\uparrow + 3H_2O + 2CO + Heat \tag{2}$$

Charcoal-producing efficiency (CPE) was also determined through the hydrolysis process of the two types of wood above. Four specimens of the two types of wood above were determined for fresh mass. After the hydrolysis process of 25 days in the kiln, their dry (charcoal) mass was determined. Based on this recorded data, the CPE was calculated using Formula (3):

$$CPE = \frac{\text{Charcoal mass}}{\text{Fresh mass of wood}} \times 100 \tag{3}$$

2.4. Reduction Method of Air Pollutants

The treatment process of pyrolysis gases (fume) emitted from a charcoal kiln is illustrated in the flowchart (Figure 2a). The fume emitted from four fume-exhausting hollows of the charcoal kiln (1) was collected by the fume hoods accordingly, then it entered the treatment tower (3) by passing through the pipe lines (2) (Figure 2b). Inside the treatment tower, a solution of water and sodium hydroxyl was sprayed in a top-down direction with fine drops by the nozzles. Pollutants in the fume were contacted and diluted into the solution. Hereafter, they were settled down to the base of the tower and contained in a settling tank before being discharged into the environment. Treated air passing the treatment tower was emitted into the atmosphere by the stack. This air pollution treatment experiment was performed at a different charcoal kiln compared to that of the experiment on the assessment of pollutant emissions from the carbonization process. Pollutants emitted from the kiln on the final days of the carbonization process were sampled at the inlet and outlet of the treatment tower. The air quality parameter CO was selected to assess the reduction efficiency of the treatment system.

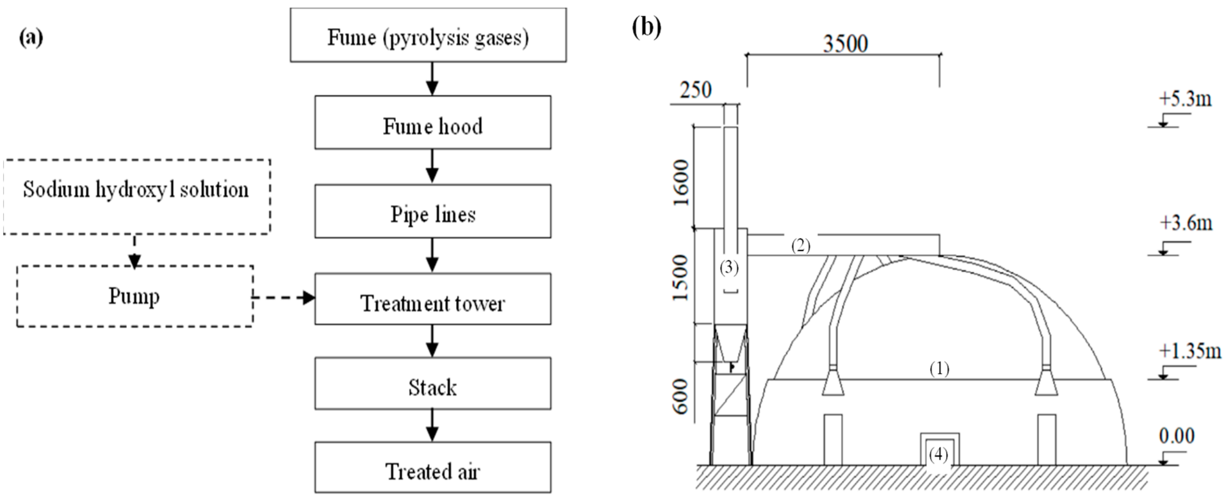


Figure 2. Flowchart (**a**) and the structure (**b**) of the air pollution treatment system. Note: (1) Charcoal kiln; (2) Pipe lines; (3) Treatment tower; (4) Heating gate.

2.5. Data Analysis

Data recorded from household interviews such as the local inhabitants' income, charcoal production, impacts of charcoal-making activities on human health and ambient environment were statistically described using Microsoft Excel 2019 software. Concentrations of pollutant gases (i.e., CO, NO_2 and SO_2) emitted from the charcoal kiln and the outlet of the air pollution treatment system were estimated based on the Vietnamese technical regulation on industrial emission for inorganic substances and dusts (QCVN 19:2009/BTNMT).

3. Results and Discussion

3.1. Effects of the Traditional Charcoal Production

Household interviews were conducted with 70 households making charcoal and 70 households not making charcoal in the study site. The livelihood of the households not making charcoal depended mainly on gardening work or hired labor at the charcoal-making households. There was a difference in the gender proportion between the households making and not making charcoal, being 67.1% and 44.3% male, respectively. This difference could be because charcoal-making work is difficult, and involves significant effects on human health. Therefore, it is more suitable for male than female labor.

The majority of interviewed charcoal makers (74.3%) responded that charcoal-producing work creates a relatively stable income for the local inhabitants. The average income of each charcoal-making kiln's owner was approximately 12 million Vietnam Dong (≈522 $US) per month; while the average income of an employee working at the charcoal making kilns was 5 million Vietnam Dong (≈217 $US) per month. The interview results show that the employees working at the charcoal making kilns accounted for 14% of responders.

According to the interview results of 70 households not making charcoal, 54 households grew fruit trees, of which the cultivation area occupied 25% of the total orchard's area of the study site. The average income from fruit tree cultivation was 5.83–6.67 million Vietnam Dong (≈253.48–290.00 $US) per month. However, information collected from the interviews pointed out that the cultivation area and yield of fruit trees have been decreased gradually due to the impact of air pollutants emitted from the surrounding charcoal kilns. More than 80% of fruit tree-growing households responded that the smoke of charcoal kilns has adverse impacts on the yield of fruit trees and the ambient environment. Smoke adhered to the leaves and stems of fruit trees, resulting in a slower development of the plants and reducing the quality of their fruits. Interview results revealed that 54.30%, 5.71%, 22.90%, 2.79%, and 14.30% of respondents agreed, respectively, that smoke either extremely, highly, fairly, little, and hardly affects the development and yield of fruit trees.

The health of the inhabitants living in the areas surrounding charcoal kilns is most substantially considered. The interview results for both inhabitants making charcoal and not making charcoal showed that about 35% of respondents were frequently faced with serious health problems, mainly diseases such as pneumonia, rhinitis, and eye inflammation. Of the respondents, 30 inhabitants (61%) confirmed that their health problems were directly related to the charcoal-making activity. These inhabitants were employees or owners of the charcoal kilns. The interview results revealed that 95% of charcoal makers are not equipped with personal protection equipment while working at the charcoal kilns. People who were frequently exposed to an environment with a high air temperature, high concentration of poison gases and charcoal dusts could be faced with the risk of health problems. According to Jacobson et al. [8], young children could be adversely affected by air pollution from biomass burning, mainly for lagged exposures with particulate matter and black carbon. The charcoal workers working in the charcoal kiln are faced with many potential health problems, such as physical injury, dizziness, eye irritation and lung diseases [10]. Workers exposed to CO for a long time often present symptoms such as headaches, dizziness, and nausea [11]. Household heating via coal combustion is a potential source of air pollution, with negative effects on human health in the rural residential zones [12,13]. The emission of SO_2 and $PM_{2.5}$ from coal combustion considerably impacts the air quality of the environment [14].

3.2. Structure of the Charcoal Kiln and the Carbonization Process

All charcoal kilns at the study site were structured in the shape of a semi-sphere and were built with baked clay bricks and mud sand mortar. A kiln included two gates: one for heating kiln and another for the loading of wood and unloading of charcoal (Figure 3). The size of the heating gate was approximately 0.6 × 0.5 m (width × height), and a concrete segment of 1 m in length was connected to the gate. A wall was located opposite to the gate inside the kiln to prevent fires. The size of the loading/unloading gate was approximately

0.75 × 2.0 m (width × height). Four fume-exhausting hollows were located at the quarter of the kiln. Their heights were about 1 m and the hollow's top was a square with a size of 0.1 × 0.1 m.

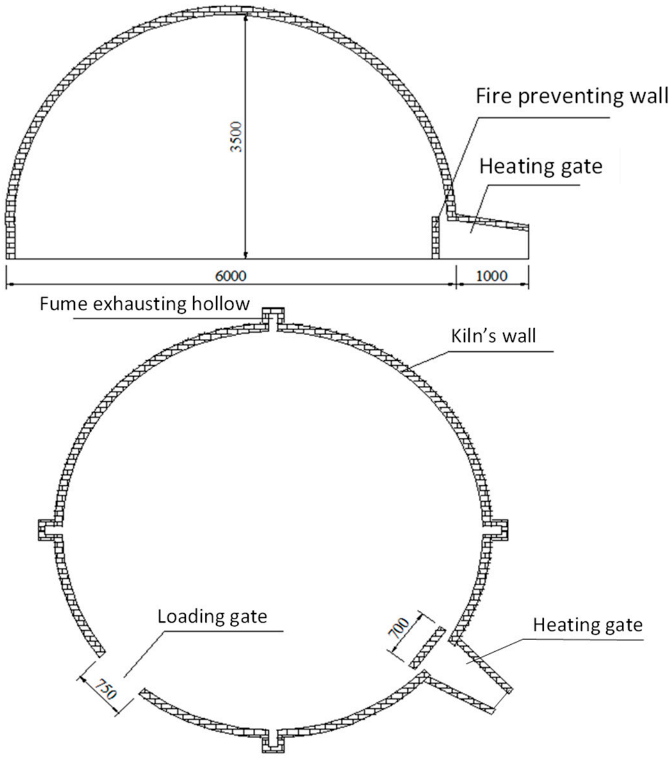
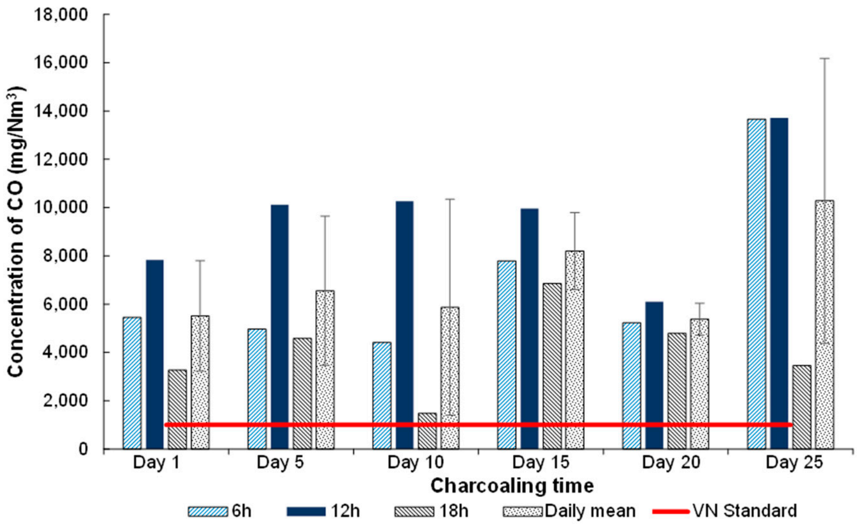


Figure 3. Structure of the charcoal kiln.

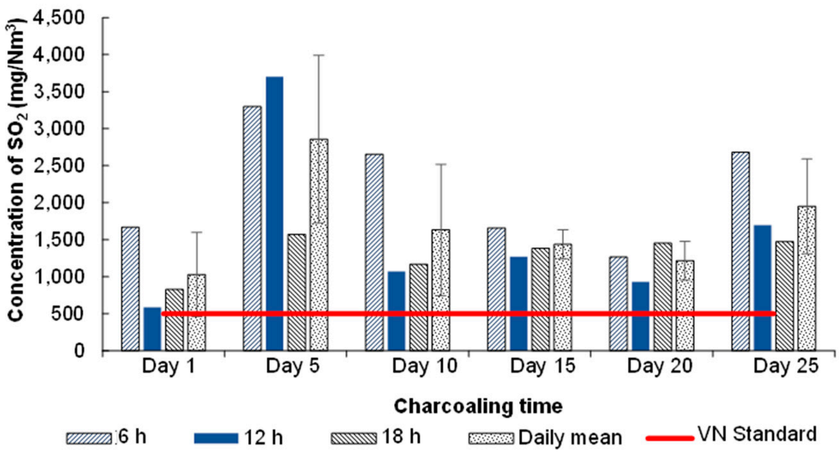
The carbonization process of a kiln was started by loading and filling the kiln with fresh wood. The loading/unloading gate was then closed by baked clay bricks and a mixture of mud and sand mortar. Thereafter, the kiln was heated by burning wood for startup at the heating gate. The hydrolysis process was started and sustained until all the fresh wood had completely turned into charcoal. Then, the heating gate was closed and the fume-exhausting hollows were also sealed. The kiln was allowed to cool and then the unloading gate was ready to open for unloading charcoal. A carbonization process could be prolonged from 20 to 30 days depending on the volume of the kiln, operating conditions, and type of wood. Charcoal-making time is also dependent on the type of kilns. For example, the charcoal-making time of earth mound kilns in Kenya is from 5 to 10 days, whilst that of a hot-tail kiln or a surface kiln in Brazil is from 2 to 4 days [7].

3.3. Determination of Air Pollutants Emitted from the Charcoal Kiln

Air pollution from the charcoal kiln was assessed based on the concentration of pollutants emitted from the kiln. Air pollutants including CO, NO_2 and SO_2 were measured at a fume-exhausting hollow for six sampling periods over the 25-day duration of the carbonization process. Measured results show that the concentration of NO_2 did not exceed the allowable level B of the Vietnamese technical regulation on industrial emissions for inorganic substances and dusts (QCVN 19:2009/BTNMT). Meanwhile, the concentrations of CO and SO_2 exceeded the Vietnamese standard and were particularly high on the final days of the carbonization process. The average concentration of CO measured on day 25 was 10,227.48 mg/Nm^3, exceeding the standard 10.2 times (Figure 4a). The average concentration of SO_2 was 1949.79 mg/Nm^3, 3.9 times higher than the standard (Figure 4b).



(**a**)



(**b**)

Figure 4. Concentrations of CO (**a**) and SO_2 (**b**) measured at various periods in the charcoal-making process.

This could be because the carbonization process was still taking place inside the kiln at this day, but the fume exhausted from the kiln was recognized as more transparent than that of previous days. The emission of gases and incomplete combustion products from the kiln is similar to the phenomena described in the study of Vilela et al. [6] during the carbonization process. The average concentration of CO was low in the early days of the carbonization process because the temperature was low and the oxygen concentration was high in the kiln. Then heat generated from the hydrolysis process caused an increase in temperature inside the kiln. Therefore, the concentration of CO gradually increased in the subsequent days. On day 25 of the carbonization process, the hollows were sealed partially. Consequently, the oxygen concentration inside the kiln was lower, and therefore the concentration of CO suddenly increased and rapidly decreased several hours later. The oscillation of the SO_2 concentration depends on the composition and sulfur content of the wood. Sulfur dioxide is a hazardous gas in the atmosphere, it can react with water vapor in the air to produce secondary substances like sulfuric acid.

The results of particulate matter $PM_{2.5}$ measured at the measuring points show that its concentration gradually reduced at locations further away from the kiln. The northeast wind was determined with a mean velocity of 3 m/s at the measuring periods. The concentration of $PM_{2.5}$ was determined to be up to 1798 μg/m^3 at the kiln, while 10 m away from the kiln, particulate matter concentration dropped to 198 μg/m^3. At the distances of 50 m and 100 m from the kiln, $PM_{2.5}$ was increased with concentrations of 262 and 203 μg/m^3, respectively. This increase could be due to a combination of particulates emitted from the target kiln and surrounding kilns. However, the concentration of $PM_{2.5}$ decreased to 72 μg/m^3 when measured 200 m from the kiln. This reduction was most likely caused by diffusion in the air and partial absorption of dust by plants in the surrounding orchards and other receiving surfaces. However, the $PM_{2.5}$ concentration value was still higher than the daily average allowable threshold of the Vietnamese technical regulation on ambient air quality (QCVN 05:2013/BTNMT, 50 μg/m^3). When measured 300 m from the kiln, the concentration of $PM_{2.5}$ was low and did not exceed the standard. Furthermore, at 1200 m, the concentration of $PM_{2.5}$ ranged from 16 - 19 μg/m^3. The diffusion of particulate matters emitted from the kiln depends on the properties of the emission source and atmospheric conditions (i.e., wind velocity/direction, air temperature . . .), plants and other receiving surfaces. The particulate matter $PM_{2.5}$ of the carbonization process is a hazardous substance and poses adverse effects on human health [15], especially for children [9]. Particulate matter $PM_{2.5}$ can also adhere to plants and negatively affect the growth and the yield of fruit trees.

3.4. Estimation of CO_2 Emission

The charcoal-producing efficiency of two types of wood, *Rhizophora* and *Eucalyptus*, at two various stages was calculated accordingly in Table 1. It could be seen that the CPE was different between the two types of wood and among the various ages as well. The CPEs of the 25-year *Rhizophora* and the 5-year *Eucalyptus* were 30.2% and 21.2%, respectively. These CPE values were determined based on the results of charcoaling 1 kg of wood, from which 302 and 212 g of charcoal are produced, depending on the type of wood. The CPEs of the remaining types of wood can be determined similarly.

Table 1. Mass of the charcoals and the charcoal-producing efficiency.

Types of Wood	Fresh Mass of Wood Specimens (g)	Produced Charcoal Mass (g)	Charcoal Mass (g)/1 kg of Wood	CPE (%)
25-year *Rhizophora* (R25)	4100	1240	302	30.2
10-year *Rhizophora* (R10)	2200	550	250	25.0
10-year *Eucalyptus* (E10)	3300	810	245	24.5
5-year *Eucalyptus* (E5)	1300	276	212	21.2

Results from studies in the literature also found that the production efficiency of charcoal depends on the operation method of the kiln [5] and the type of the kiln [7]. Okello et al. [16] found that the efficiency of conversion from wood to charcoal for *Acacia drepanolobium* wood in Laikipia, Kenya, ranged from 10.2 to 18.2%. However, technically improved kilns could result in a high CPE. For example the Mark IV, Cusab Kiln, and Gayland Batch charcoal "retort" give efficiency rates of 25 to 32% [17]. A new ecological retort system developed for the charcoal industry in the Eastern Mediterranean can produce charcoal without emitting air pollutants, and its CPE is 32.0 $\pm$ 1.5% [18]. The carbonization process emitted not only CO_2 and CO gases, but also other contamination substances such as particulate matters, SO_2, NO_x, etc. This experiment only focused on determining the loading of CO_2 and CO - greenhouse gases contributing to global warming.

The loading of CO_2 and CO emitted from charcoaling 1 kg of wood in Table 2 were calculated based on the results of a fresh biomass-drying experiment and the incomplete combustion Equation (2). For the 25-year *Rhizophora* wood, based on the results of the drying experiment, when 1 kg of this type of wood was charcoaled in the charcoal kiln, 849.15 g of water vapor, 691.90 g of CO_2, and 880.60 g of CO are produced according to the incomplete combustion equation. The loading of CO_2 and CO emitted from charcoaling 1 kg of the other wood types were calculated similarly.

Table 2. Loading of CO_2 and CO emitted from charcoaling 1 kg of wood.

Types of Wood	Loss of Water Vapor (g)	Emitted CO_2 (g)	Emitted CO (g)
25-year *Rhizophora* (R25)	849.15	691.90	880.60
10-year *Rhizophora* (R10)	889.89	725.10	922.85
10-year *Eucalyptus* (E10)	886.86	722.63	919.71
5-year *Eucalyptus* (E5)	909.96	741.45	943.66

Based on the results of the carbonization process and CPE found in Table 1, it can be seen that when 1 kg of 25-year *Rhizophora* wood was charcoaled, 302 g of charcoal is produced. And as presented in Table 2, charcoaling 1 kg of 25-year *Rhizophora* wood produced 691.90 g of CO_2 and 880.60 g of CO, which are emitted into the air. It is implied that when 302 g of charcoal is produced from 1 kg of 25-year *Rhizophora* wood, 691.90 g of CO_2 and 880.60 g of CO were emitted from the carbonization process. It can thus be estimated that 1 ton of 25-year *Rhizophora* charcoal which is produced from the carbonization process emits 2.291 tons and 2.916 tons of CO_2 and CO, respectively. Similarly, when 1 ton of 10-year *Rhizophora*, 10-year *Eucalyptus*, and 5-year *Eucalyptus* charcoal is produced, the loading of CO_2 emitted from the carbonization process is 2.900 tons, 2.950 tons, and 3.497 tons, respectively. It can be recognized that the loading of CO_2 emitted from producing 1 ton of 25-year *Rhizophora* charcoal was 1.27, 1.29 and 1.53 times lower than that of 10-year *Rhizophora*, 10-year *Eucalyptus*, and 5-year *Eucalyptus*, respectively.

It can be concluded that as the age of the wood used for carbonization increases, the charcoal mass increases and the loading of pollutant gases (i.e., CO and CO_2) emitted decreases. On the other hand, the higher the age of the wood, the less the mass of firewood is used at the heating gate of the kiln, because it could have a higher carbon content contained in the wood used in the carbonization process. This approach not only increases the profits to charcoal makers but also reduces adverse human health and environmental effects.

3.5. Air Pollutant Reduction Efficiency of the Air Pollution Treatment System

Air pollutants exhausted from the four fume-exhausting hollows of the kiln were collected by fume hoods and transported to a treatment tower through the composite pile lines as illustrated in Figure 2b. Inside the treatment tower, a solution of water and sodium hydroxide was sprayed into fine droplets through nozzles. When air pollutants contacted the solution inside the tower, they were partly absorbed/diluted into the solution and dropped to the base of the tower, and treated air flux discharged into the atmosphere through the stack of the system. Pollutants at the base of the tower were considered wastewater and needed to be treated in further research.

The composite fume hoods of the pyramid shapes were located 0.2 m above the fume-exhausting hollows. The space between the fume hood and the fume-exhausting hollow was covered by a nylon sheet to limit the release of smoke. The composite treatment tower applied wet method was mainly structured with a cyclone part of dimensions 0.6 × 1.5 m (diameter × height) and a funnel part at a height of 0.6 m. The total volume flow rate of the solution sprayed through the nozzles inside the tower was 40 L/h. The concentration of sodium hydroxide solution was 50 mg/L with a pH of approximately 9.5.

The treatment efficiency of the air pollution-controlling system was estimated through three consecutive measuring days. In this study, *Eucalyptus* was used as raw material for producing charcoal. The carbon monoxide treatment efficiency of the system was assessed based on its concentration measured at the inlet and outlet of the system. On day 15, the concentration of CO measured at the inlet was 3869 ± 288.1 mg/Nm^3. After passing the treatment tower, the concentration of CO in the treated air decreased by 2247 ± 43 mg/Nm^3. Concentrations of CO in the fume rapidly increased on days 16 and 17. During these periods, the average CO concentration measured at the inlet of the treatment system was 5679 ± 654.8 mg/Nm^3 and 13,004 ± 423.3 mg/Nm^3, and at the outlet they were 3298 ± 5.3 mg/Nm^3 and 7549 ± 52.7 mg/Nm^3, respectively. The carbon monoxide treatment efficiency of the system was calculated to be 41.93%, on average, for the duration of the measurement. After being treated by the system, the carbon monoxide concentration still exceeded the allowable limit of the Vietnamese standard (1200 mg/Nm^3). The study results show that the sodium hydroxide solution had a low efficiency in absorbing the carbon monoxide from the fume emitted from the charcoal kiln. Theoretically, carbon monoxide is only efficiently absorbed by specific solutions such as liquid nitrogen and cuprammonium solution. However, these solutions are not suitable for the air pollution treatment system in this study site due to their high investment costs. Throughout the world, especially in Africa, pollutant emissions from traditional charcoal-making kilns are not usually treated by technical systems [7]. A reduction in emissions from the charcoal industry was applied for technically advanced kilns [6,19]. Moreover, according to the study of Sparrevik et al. [19], the mean emission factors for the retort kilns using identical feedstock consisted of carbon dioxide (CO_2) = 1950 ± 209 g/kg charcoal, carbon monoxide (CO) = 157 ± 64 g/kg charcoal, and total solid particles (TSP) = 12 ± 18 g/kg charcoal. The corresponding value for the non-retort kilns tested was generally higher; 2380 ± 973 g/kg of charcoal, 480 ± 141 g/kg of charcoal, and 7.9 ± 2.6 g/kg of charcoal for CO_2, CO, and TSP, respectively.

4. Conclusions

The obtained results show that the traditional carbonization process emitted hazardous substances, such as particulate matters and incomplete combustion gases. Compositions and concentrations of these air pollutants varied over the operation time of the charcoal kiln. The concentrations of carbon monoxide and sulfur dioxide emitted from the kiln exceeded the allowable limit of the Vietnamese technical regulation on industrial emissions for inorganic substances and dusts. The experiment results revealed that the air pollutant concentrations and charcoal-producing efficiency depended on the age and type of wood. If the wood used in the carbonization process was younger, a higher amount of emission gases was produced, and a lower efficiency was achieved for the charcoal-making process. Particulate matter $PM_{2.5}$ concentrations emitted from the kiln decreased with the main wind distance from the kiln, as it diffuses in the ambient environment. However, it could still have negative effects on public health and the environment.

The air pollution treatment system applying the wet method with a sodium hydroxide solution likely removed the carbon monoxide from the fume flux of the charcoal kiln. However, the concentration of carbon monoxide in the outlet of the system still exceeded the Vietnamese standard. Otherwise, the system is rather simple and suitable to apply at the study site; further research is needed to find an optimum solution for protecting public health and the environment from the adverse effects of charcoal production activities.

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Appendix A

QUESTIONAIRE ON
SURVEYING THE ENVIRONMENTAL SITUATION, HEALTH, AND LIVELIHOOD AT HOUSEHOLD LEVEL

I. For households with making charcoal

A. ***General information***
B. ***Information about households with making charcoal***
   1. When did charcoal production started at household level at your family?
   2. How many charcoal kilns are in your house?
      2.1 Volume of charcoal kiln (for each kiln)?
      2.2 How long does it take to finish a charcoal making process (from loading fresh wood to unloading charcoal stage)?
      2.3 How many the charcoal batches are produced a year?
      2.4 What factors does the time to complete a charcoal batch depend on (type of woods, weather condition, type of fuel woods . . .)?
      2.5 What kind of material wood is used to make charcoal?
      2.6 How much is investment cost for making a batch of charcoal?
      2.7 How much is the average income from a batch of charcoal?
   3. In your opinion, does the charcoal production bring a stable income?
   4. How about demand for organizing a charcoal production model (it could be gathered into cooperatives to stabilize inputs and outputs of the production)?
   5. How is the situation of controlling fume/smoke emitted from the charcoal kiln?
   6. In your opinion, does charcoal production cause any difficulties or disadvantage?
   7. Please talk about your current health status?
   8. Have you ever got any of the following diseases since the past 20 years?
   9. What should be done to reduce environmental pollution from charcoal production?
   10. If you are forced to stop charcoal production, do you have any comments?

I. For households without making charcoal

A. ***General information***
B. ***Information about households without making charcoal***
   1. Does your family grow fruit trees? (Please tell us about the name of fruit trees)
      1.1 If you plant fruit trees, could you please let us know about the area planted?
      1.2 If you plant fruit trees, could you please tell us the cost to take care of the orchard in one season?
   2. In your opinion, do charcoal making kilns located surrounding your house emit air pollutants?
   3. In your opinion, do air pollutants emit from the charcoal making kiln surrounding your house impact on the fruit trees?
      3.1 If yes, could you please tell us what the impact is?
      3.2 If yes, could you please tell us the extent of the impact?
   4. Could you please tell us about your current health status?
   5. Have you ever got any of the following diseases since the past 20 years?
   6. In your opinion, do air pollutants emit from the charcoal kilns impact the surrounding people health?
   7. If yes, could you please tell us the extent of the impact?
   8. If yes, could you please tell us who is more susceptible to health effects?
   9. Do you have any comments related to operation of the surrounding charcoal kilns?
   10. What suggestions do you have about the charcoal production at the area you live?

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