applied system innovation

MDPI

Article

Treatment of Infectious Waste through the Application Rotary Kiln Incinerators and Ozone Technology

Khomson Khannam [1], Wenich Vattanapuripakorn [1], Sathapon Sonsupap [1], Jiradanai Sarasamkan [2], Umakorn Tongsantia [3] and Bopit Bubphachot [4,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Mahasarakham University, Mahasarakham 44000, Thailand; khomson.57.2002@gmail.com (K.K.); doctorwenich@gmail.com (W.V.); sathapon.son@msu.ac.th (S.S.)
[2] Department of Radiology, Faculty of Medicine, Khon Kaen University, Khon Kaen 40002, Thailand; jirasar@kku.ac.th
[3] Department of Public Health Administration, Faculty of Public Health, Khon Kaen University, Khon Kaen 40002, Thailand; t_umakorn@kkumail.com
[4] Heat Pipe and Thermal Tools Design Research Unit (HTDR), Faculty of Engineering, Mahasarakham University, Mahasarakam 44000, Thailand
* Correspondence: bopit.b@msu.ac.th

Abstract: The alarming rate at which infectious waste is growing was an unsolved problem worldwide before the pandemic, and it has only gotten worse. It is especially prominent in the medical services, owing to the improper use or the lack of high-efficiency waste management systems. To address this issue, this paper presents a modification to the conventional rotary kiln incineration method using add-on ozone (O_3) at a concentration of 100–160 g/h in order to enhance its efficiency when treating emitted air pollutants. These pollutants of Hg, HF, TSP, SO_2, NO_2, CO, and HCl were measured, and their percent opacity concentrations were 0.006 mg/m^3, 0.680 mg/m^3, 21.900 mg/m^3, 5.600 mg/m^3, 16.300 mg/m^3, 13.700 mg/m^3, 0.022 mg/m^3, and 6%, respectively. The amounts of these air pollutants were considerably lower than those released from a rotary kiln incinerator without the add-on ozone. Additionally, all the measurements were lower than the emission thresholds established in the US Environmental Protection Agency Emission Standards Reference Guide. Therefore, using the proposed rotary kiln incineration method modified with add-on ozone is suitable for use in the elimination of infectious waste in that it drastically reduces air pollution and improves air quality, resulting in environmental improvements aimed at mitigating the devastating impacts pollution has on human health.

Keywords: ozone; infectious waste; rotary kilns; air pollution; standards

Citation: Khannam, K.; Vattanapuripakorn, W.; Sonsupap, S.; Sarasamkan, J.; Tongsantia, U.; Bubphachot, B. Treatment of Infectious Waste through the Application Rotary Kiln Incinerators and Ozone Technology. *Appl. Syst. Innov.* **2021**, *4*, 71. https://doi.org/10.3390/asi4040071

Academic Editor: Igor Korobiichuk

Received: 13 August 2021
Accepted: 20 September 2021
Published: 26 September 2021

1. Introduction

Increasing amounts of waste are considered a major global problem that tremendously impacts the environment and human life. For example, air pollution is an inevitable consequence of waste incineration, and water pollution is caused by the disposal of waste, harmful substances, and the release of industrial sewage into rivers, resulting in severe environmental degradation. This problem is further complicated by an ever-increasing amount of infectious waste resulting from the COVID-19 pandemic, which the world has been facing for almost 2 years. The pollution of infectious waste, especially from hospitals and industries, also posed serious risks to humans, animals, and plants. The volume of waste produced per day by the human population of Thailand increased during 2014–2018; the amount of waste generated during each consecutive year in this period was 71,779, 73,560, 74,130, and 76,529 tons/day [1]. This increase in the amount of waste was partly caused by the increase in the amount of infectious wastes. According to the Pollution Control Department's report from 2013–2017, the annual amounts of infectious waste were 50,481, 52,147, 53,868, 55,646, and 57,954 tons, respectively. The current disposal technique for infectious waste is incineration, which utilizes various approaches such as the pyrolysis method, the high-temperature steam sterilization method, the chemical disinfection method, the microwave disinfection method, and rotary kilns [2]. According to the standards set by the Department of Health's Ministry of Public Health, small kilns can eliminate infectious waste at rates of 25, 50, and 100–150 kg/h. A rotary kiln with a 3-burner system installed has a combustion temperature of approximately 700–1000 °C, and the high temperature results in the suppression of dioxins and furans [3] and allows for the decomposition of other dioxins' synthesis [4,5]. Proper incineration of contaminated material is currently the best available method for preventing and controlling exposure to dioxins and requires high temperatures of over 850 °C. For the destruction of large amounts of pollutants contaminated by exhaust gas, even higher temperatures are required. One further enhancement is when an O_3 system [6] and chiller have been installed in order to control the temperature of cold water in the wet scrubber room for treatment, as it is the most efficient method for ozone gas oxidation. Ozone is a strong gas phase oxidant that can achieve pre-oxidation at low temperatures of 15–20 °C, which is significant for this investigation [7,8]. Additionally, and of great concern, is the fact that the kilns are not designed to eliminate dust and smoke. The Public Health Ministry Report of 1999 showed that only 41% of hospital infectious waste incinerators around the world are functioning properly, whereas the rest do not [1]. Regarding the provincial infection waste management in Thailand, there is a total of 820 public hospitals under the governance of the Ministry of Public Health. Among these, only 723 hospitals are equipped with incinerators for the disposal of infectious waste. This would imply that 97 hospitals do not have the facilities required for the disposal of infectious waste. Provincial administrative offices are responsible for managing the infectious waste generated in these hospitals. The waste is collected and combined with other solid waste from locations with a similar lack of disposal capabilities. After collection, they are processed together at disposal facilities provided by the local government administrative organizations. However, the disposal of infectious waste by incineration releases emissions such as particulate matters (PM), opacity, carbon monoxide (CO), dioxins and furans, hydrochloric acid (HCl), sulfur dioxide (SO_2), nitric oxide (NO_x), lead (Pb), cadmium (Cd), and mercury (Hg) into the atmosphere [9–11]. The inadequacies in current hospital waste management practices are mainly related to ineffective segregation at the source, inappropriate collection methods, unsafe storage of waste, insufficient financial and human resources for proper management, and poor control of waste disposal [12]. Infectious waste can act as a major breeding ground for germs that can adversely affect human beings. The removal of such pathogens growing on infectious waste can be achieved using methods such as steam sterilization, thermal inactivation, sterilization by irradiation, use of chemical disinfectants (e.g., sodium hypochlorite), microwave treatment, and vapor sterilization (e.g., ethylene oxide, formaldehyde, and ozone (O_3)) [13]. Corona discharge in a dry process gas containing oxygen is presently the most widely used method of ozone generation for water treatment. A typical production line is composed of the following units: a gas source (compressors or liquefied gas), dust filters, gas dryers, ozone generators, contacting units, and off-gas destruction [14]. Currently, the use of a rotary kiln and O_3 for disinfection and the burning of waste is becoming increasingly popular, as evidenced by previous studies showing the growth in employing O_3 to disinfect bacteria, viruses, fungi, vegetative bacteria, mycobacteria, and bacterial spores [15,16]. In addition, O_3 has been used to treat wastewater more effectively than previous methods [17–19]. Infectious waste management presents a significant challenge to human health, especially with the improvement in and development of new technologies, achieving sustainable reduction of emissions to zero waste can be a reality. A low-temperature oxidation process using ozonated water has been developed for the chemical conversion of organic wastes to CO_2 and H_2O. Experiments were conducted to evaluate the rate and effectiveness with which ozone oxidized several different types of waste [20]. A greater flow of ozone and agitation of the ozonated water system also increased the processing rates. This research studies the efficiency of a rotary kiln utilizing a three-burner system combined with the processes of ozonation for the treatment of pollutant substances emitted by infectious waste incineration [21].

In developing infectious waste incineration technology, it is crucially important to enhance the combustion efficiency of the pollution treatment. Currently, rotary kilns are a well-known approach used for the incineration of infectious waste. These kilns are designed for incineration in compliance with the U.S. EPA principle of using a temperature exceeding 700 °C. The procedure is specifically designed to involve two rounds of combustion. In order to achieve complete combustion, these kilns are also equipped with an exhaust emission elimination system that employs a wet scrubber so that incinerating infectious waste by using this method can reduce the amount of pollution released into the atmosphere [22]. Innovation in waste treatment and the techniques discussed in this paper will offer considerable help in tackling the issue of pollutants being released into the environment [23]. The purpose of this manuscript is both interdisciplinary and mixed. It focuses on a comparative analysis before and after installation of the three-burner rotary kiln with an O_3 system [24]. It was revealed that the process of combining oxidation O_3 and low temperatures of around 15–20 °C by the chiller machine led to the exhaust gas being significantly diluted in the concentration of the pollutants. When compared with previous research [25], the results suggested that the rotary kiln with a three-burner system installed along with the O_3 application was more efficient. Furthermore, the level of pollutant gas emissions decreased significantly when measured by using the U.S. EPA and Thai standards. The treatment method resulted in nearly zero pollutants being released. Therefore, the application of the O_3 treatment method in infectious waste incinerators needs further study to be made practical for industries.

2. Materials and Methods

2.1. Rotary Kiln Infectious Waste Incinerator

The design of this rotary kiln incinerator also takes into consideration the inefficiencies and reduces exposure to service personnel by employing a front load infeed system. An automatic belt feeds the solid waste into the incinerator, with the infectious waste moved into the channel where a hydraulic press pushes the waste into the rotary combustion chamber, which functions without the need for operator contact. As a further safety precaution, there is also a double door system with a cover to prevent smoke and heat from escaping. It also includes a system to extract the smoke from the incinerator room for re-burning. In the next step of the incineration process [26], the operation of this infectious waste feed system can be operated either autonomously or semi-autonomously. The rotary kiln incinerator used in this experiment was developed from combustion furnace technology in Japan and was designed to achieve the highest possible efficiency for incineration systems used to dispose of infectious waste. The several recent improvements to the incinerator system in this study are described below and shown in Figure 1.

For the front gate of the primary chamber, the combustion temperature is 700–1000 °C. Air-filling waste is heated and volatilized in the primary chamber. The disposal of infectious waste to be burnt enters through a system on the left and right sides of this chamber, which facilitates the pumping of air into the chamber.

(1) An aeration fan is used to inject and move air into the combustion chamber, which is designed to have air flow through the front and back pipes to equalize the air flow from both sides.
(2) The secondary chamber is used for the second round of exhaust gas combustion for eliminating gas pollution (e.g., dioxins and furans). The chamber maintains the desired combustion temperatures above 850–1000 °C to enhance the efficiency of gas pollutant suppression.
(3) The third chamber is used for the final round of exhaust gas combustion to eliminate gas pollution (e.g., dioxins and furans). This chamber also maintains the desired combustion temperatures above 850–1200 °C. Subsequently, the remaining gases flow to a cyclone separator, where dust and small particles are trapped.

(4) The cyclone separator functions as a dust collector; it typically employs centrifugal force, a form of inertia, to force the air containing dirt and dust through a vertical cylinder with a cone-shaped bottom. As the air continues to spin, the heavier particles of dirt and dust begin to separate from the other debris and move outward toward the walls of the chamber. Thereafter, they slide to the bottom of the container and into the dust bin. Alternatively, the pollutant gases flow upward to the top of the cyclone pipe, and the air pressure is increased using an aeration fan.

(5) The aeration fan uses a high-pressure 0.5 horsepower pump to increase the pressure of the remaining gases after combustion and move them from the cyclone separator toward the wet scrapper.

(6) Gas scrubbing collects the dust and small particles that pass through the cyclone separator. The gas then flows through from the side of the tank above water onto the cooling pad in the opposite direction. Water at a temperature of 15–20 °C is sprayed from the top toward the steering wheel that directs the flow to the activated charcoal, which absorbs toxic gases and odors such as methyl sulfide.

(7) In a gas treatment chamber with high oxidation reaction, most types of microbes are killed, in particular the most dangerous bacteria which pose the greatest threat to human health. Odors, chemical compounds, and toxic gases are also eliminated using the treatment in this chamber before the remaining gases are released into the atmosphere.

(8) The combustion gas vent has a measurement point set at a height of 10 times that of the diameter of the vent. The measurement point is installed to check the quantity and quality of the treated gases before they are released out into the environment. As the system is heated via combustion, cold water is used to treat the polluting gases.

(9) The cool water tank stores the cool water required for injection from a nozzle during gas scrubbing. The water gate adjusts and mixes the water containing heat and toxic gas before this water enters the cool water pump. A small portion of the warm water is subsequently released into the warm water tank.

(10) The warm water tank stores warm water that is heated by the absorbed pollutants from the exhaust gases produced via combustion. The debris is dropped to the bottom of the tank and subsequently disposed of. Thereafter, clean water is fed to a chilling machine.

(11) The chilling machine produces cold water that is to be stored in the coolant tank before being sprayed into the scrubbing tank. Once the water absorbs the heat, leading to an increase in its temperature, it is circulated back to the chiller to be cooled again as shown in Figure 1.

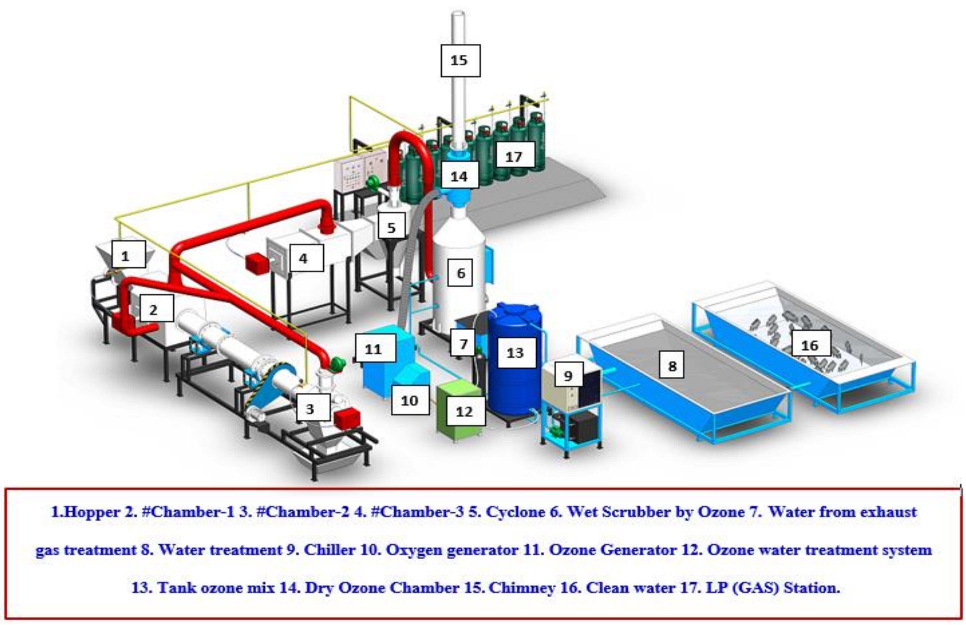

Figure 1. Rotary kiln incineration and O_3 system diagram [8,24,27].

2.2. Energy Consumption and Operating Cost Analysis

The cost should be calculated by all organizations, as it is a useful metric for assessing the overall cost of technology and investment. To properly assess the cost, the energy consumption in all systems and for all functions must be taken into consideration along with the cost of the system downtime as shown in Table 1 [28].

Table 1. Energy consumption and operating cost analysis.

Parameters	Value (USD)
Energy Cost of Electricity (Unit)	0.12
Energy Cost of Water (Unit)	0.48
Energy Cost of Fuel (Lite/Unit)	0.36
Operation Cost for 4-Person Staff (Month/20,000) = (80,000) (THB)	2447
Cost of the Technology/(THB)	
Ozone Technology Cost (Size 100–160 g/Nm^3) (Sets) = (2,000,000)	61,180
Rotary Kiln Technology Cost (Size 100 kg/h) (Sets) = (10,000,000)	305,903
Total Cost of the Technology (Sets) = (12,000,000)	369,084
Availability (Hours)	24

Note: Data analysis in Thai baht (1 USD = 32.69 THB).

A performance measure of rotary kilns with three burners but without the use of O_3 showed it is capable of combusting 100 kg/h of infectious waste and maintaining a constant temperature of 700–1000 °C in the first chamber of the incinerator and >850–1200 °C in the second and third chambers [3]. These temperatures bring the pollutant levels lower than the emission standards defined in the Emission Standard Reference Guide recommended by the U.S. EPA. The concentrations of the air pollutants released were also lower than the emission standard (especially in the group of heavy metal gases such as Ni, which had values half of the defined standard (i.e., it measured 0.5 mg/Nm^3 when the standard value was 1 mg/Nm^3) [24].

The rotary kiln incineration system used in this experiment was developed and designed to achieve the highest possible efficiency for treatment systems used to dispose of infectious waste. The several recent improvements to the treatment system in this study are described below in (Table 2).

Table 2. Infectious waste rotary kiln incineration.

Parameters	Value
Combustion Chamber 1	700–1000 °C
Combustion Chamber 2	850–1000 °C
Combustion Chamber 3	850–1200 °C
Wet Scrubber	15–20 °C
Fuel Consumption Rate (LPG)	18–25 L/h
Waste Throughput Rate	100 kg/h
Combustion Duration	1.0 h
Airflow Throughput Rate	0.1–0.2 m^3/s
Speeds of the Rotary Kilns	0.6–1 rpm/min

2.3. O_3 Add-On into the Infectious Waste Incineration System

This study focuses on the process of incorporating the O_3 add-on into the infectious waste rotary kiln system as illustrated in Figure 2. As shown in this diagram, the O_3 gas has a 100–160 g/h capacity (or 100–160 g/Nm^3). The O_3 cell cooling process used water, with 220 V and 50 Hz produced by the ozone generator (model: OZ-100G/H; serial number: OZ 160726616). This generated O_3 with an oxygen concentration of 90 ± 3% and with a maximum power consumption of 550 W. The oxygen flow rate was 10 LPM. The oil-free air then flowed to the "mixing unit" to be mixed with the O_3-filled water that was chilled to maintain its temperature at 15–20 °C and the flow rate at 65 L/min. as shown in Table 3.

This mixing process yielded "mixed ozone water" stored in the storage tank for further use. In this study, we used O_3 for air pollution treatment in two parts. The first part was spraying the "mixed ozone water" into the polluting gases at the point where the gases entered the wet scrubber tank. This is referred to as a "wet ozone treatment". The second part of using O_3 for air pollution treatment took place in the treatment chamber, which was initially designed and built by us to incorporate suppression with pure O_3 gas oxidation before the exhaust gases are released into the atmosphere. As the process at the newly built chamber used pure O_3 gas alone without mixing it with water, we usually refer to this process as a "dry ozone treatment". The efficiency measurements of the exhaust gases' combustion from the system were processed, and the results (i.e., information related to the concentrations of the pollution gases released from the vent) were compared using the U.S. EPA standard [27].

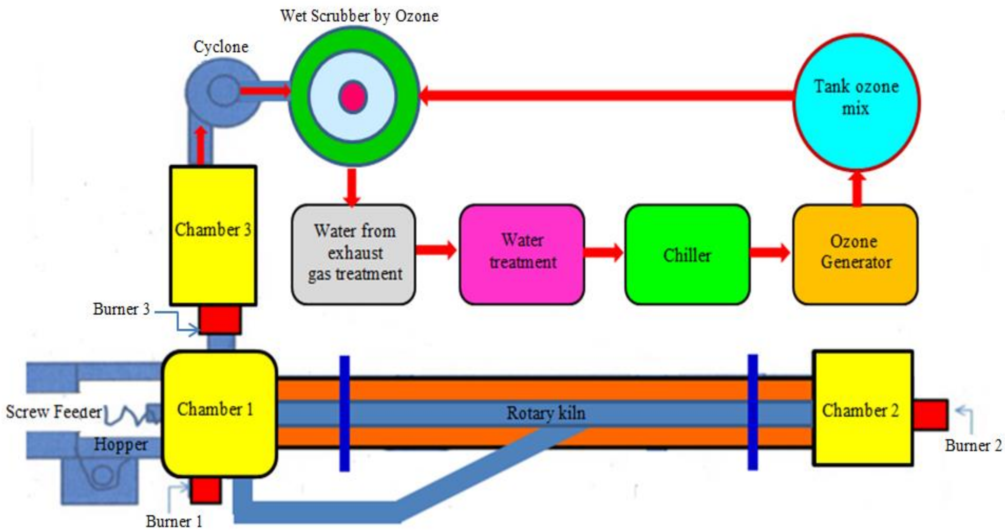

Figure 2. Schematic diagram of the rotary kiln incinerator equipped with an ozone system [8,24,27].

Table 3. Infectious waste treatment system by ozone generator [27].

Parameters	Value
Temperature in the Wet Scrubber	15–20 °C
Oxygen Consumption Rate	10 L/min
Ozone Concentration	100–160 g/Nm^3
Effect of Residence Time	3–8 s
Flow Rate Mixing	65 L/min
AC Voltage	5–10 kV
Oxidation Duration Time	0.5–5 min

The combination of adsorption followed by ozone oxidation with the rotary kiln using a three-burner system seems to be the better technology for the removal of pollution substances emitted from the contaminated materials [21]. The overall pattern of the ozone decomposition mechanism and reaction will be helpful for the implementation of its application on a large scale. We found that the concentration of the released air pollution was much lower than the standard high threshold presented. Ozone can be produced by phosphorus contact, silent discharge, photochemical reactions, or electrochemical reactions, principally proceeded by the reaction of oxygen atoms with oxygen molecules. There are side reactions to the generation of ozone, however, which are responsible for ozone depletion, including thermal decomposition and quenching reactions by reactive species. The solubility of ozone in water is much higher than that of oxygen, suggesting that it may be reliably applied in the air pollution treatment and water and wastewater treatment [8]. Based on the resonance structures of ozone, one oxygen atom in an ozone molecule is electron-deficient, displaying electrophilic properties, whereas one oxygen atom is electron-rich, holding nucleophilic properties. The superior chemical reactivity of ozone can also be indirectly revealed by radical-mediated reactions initiated from the homogeneous and heterogeneous catalytic decomposition of ozone before being used to treat pollution in the treatment system [29].

2.4. Measuring the Concentrations of Pollutants Released into the Atmosphere

Sampling of the released exhaust gases at the end of the incinerator vent was performed 2.2 m above the top end of the chimney. This process was based on the standard gas emission sampling procedure which recommends the collection of samples at a height equal to 10 times the diameter of the chimney (0.22 m). The principle of emission suction from stationary sources was used to collect and analyze the particulate air quality samples. For the sample collection in this study, the isokinetic (dry basis) sampling method was adopted. This method employs a filter cured at 105 °C at the same wind velocity during measuring to prevent the refraction of moving particles and maintain an acceptable isometric kinetic range of ±10%. The methods used for air sampling and analyses are listed. The study utilized a total of 178 kg of infectious waste, which came from hospitals, clinics, and medical establishments and was produced by medical services from a variety of treatments, including dentistry, pharmaceuticals, laboratory diagnosis, and immunization, as well as research studies conducted on humans in which there was contamination through contact with pathogens from patients or patient products. There was a clear collection process with general waste in which physical and chemical property data were analyzed before waste was put into the incinerator. The samples of infectious waste analyzed in this research were of considerable importance, because each kind of waste affected the burn and emitted different pollutants. The composition of the waste needed to be analyzed physically and chemically. Data such as weight, moisture, and density were collected. After that, each kind of waste was packed into $25 \times 30 \times 60$ cm^3 containers, and the weight of each type of waste was recorded. The bags were completely sealed when burned, and all that remained was ash after the combustion process was completed.

3. Results and Discussion

3.1. Treatment of Pollution Gases and the Efficiency of a Rotary Kiln Using a Three-Burner System and O_3

This section describes the results of the rotary kiln r using a three-burner system set at a high temperature to suppress dioxins and furans [3]. The temperature was set at 850–1200 °C, which is essential for the decomposition of PCDD/Fs [5] and should be considered in calculating the consumption rate of LP-Gas costs as shown in Table 1. The process released lower concentrations of pollution than the incineration processes that did not add O_3 into the system [30]. In comparison with the U.S. EPA standard, as shown in Table 4. the ozone oxidation process at 15–20 °C is significantly more effective [8] when used in conjunction with an oxidation process on the pollution substances [7]. Adsorption was followed by the ozone oxidation process. The adsorption was efficient in the treatment of VOCs and molecular and organic pollutants [8] Applying O_3 to the rotary kilns of three-burner systems reduced air pollution substantially. The removal efficiency of the pollutants included PCDD/Fs, Hg, Pb, Cd, HF, TSP, SO_2, NO_2, CO. Especially when the rotary kiln used a three-burner system and the secondary and third chamber were used for the final round of exhaust gas combustion, a temperature setting of 850–1200 °C was necessary for this investigation to facilitate the decomposition of PCDD/Fs [5]. The high temperature allows for the suppression of dioxins and furans, and this method also leads to a reduction in the pollution levels when compared with the standards of the U.S. EPA [3,24]. Therefore, this process complies with national sustainable development goals within the framework of global development, for which the United Nations (UN) has determined that member countries must take action in reducing air pollution by 2030 to improve the quality of life for their populations. In addition to eliminating air pollution, this treatment also reduces the water pollution that could be released from waste elimination systems.

Table 4. Methods of air sampling and analysis.

No.	Parameters	Analysis Method	Standard Value [31]
1	Mercury (Hg)	Isokinetic, Cold Vapor—ASS	0.05 mg/m^3
2	Lead (Pb)	Isokinetic, ICP-AES	1.5 mg/m^3
3	Cadmium (Cd)	Isokinetic, ICP-AES	0.5 mg/m^3
4	Hydrogen Fluoride (HF)	Ion Chromatography	16.4 mg/m^3
5	Particulate (TSP)	Isokinetic, Gravimetric	320 mg/m^3
6	Sulfur Dioxide (SO_2)	Barium Thorin Titrimetric	79 mg/m^3
7	Oxides of Nitrogen (NO_x as NO_2)	Chemical Absorption, Colorimetric	470 mg/m^3
8	Carbon Monoxide (CO)	Bag, Non-Dispersive Infrared	45.8 mg/m^3
9	Hydrogen Chlorine (HCl)	Ion Chromatography	119 mg/m^3

Note: Method Detection Limits (MDLs) of lead and cadmium are 0.19 mg/m^3 and 0.02 mg/m^3.

Applying O_3 to the rotary kilns of the three-burner systems reduced air pollution substantially. The removal efficiencies of the pollutants included PCDD/Fs, Hg, Pb, Cd, HF, TSP, SO_2, NO_2, CO. Especially when the rotary kiln used a three-burner system and the secondary and third chamber were used for the final round of exhaust gas combustion, a temperature setting of 850–1200 °C was necessary for this investigation to facilitate the decomposition of PCDD/Fs [5]. The high temperature allows for the suppression of dioxins and furans, and this method also leads to a reduction in the pollution levels when compared with the standards of the U.S. EPA, as shown in Table 5 [3,24].

Table 5. Comparison of air pollution compounds measured at the end of the infectious waste combustion air vent (mg/m^3).

Parameters	Rotary Kiln (3-Burner)	15% O_2	7.0% O_2	U.S. EPA (1) [31]
Mercury (Hg)	0.006	<0.001	<0.001	0.05
Lead (Pb)	ND (2)	ND (2)	<0.19	1.5
Cadmium (Cd)	ND (2)	ND (2)	<0.02	0.5
Hydrogen Fluoride (HF)	0.680	0.013	0.034	16.4
Particulate (TSP)	21.900	3.4	7.4	320
Sulfur Dioxide (SO_2)	5.600	<3.4	<3.4	79
Oxides of Nitrogen (NO_x as NO_2)	16.300	<2.0	<2.0	470
Carbon Monoxide (CO)	13.700	1.7	3.7	45.8
Hydrogen Chlorine (HCl)	0.022	<0.015	<0.015	119
Opacity	6%	5%	5%	10%

Note: (1) The standards for controlling the emissions of pollutants released from an infectious waste incinerator in accordance with the methods prescribed by the United States Environmental Protection Agency (U.S. EPA), burning less than 50 tons/day. ND = not detected. (2) Results of actual percentage of O_2.

3.2. Efficiency Comparison of a Rotary Kiln Using a Three-Burner System with and without an O_3 System and the Standards of the U.S. EPA

The results for incinerating infectious waste as shown in Table 6. The amount of pollutants released without the O_3 system were evaluated for the levels of TSP, CO, NO_2, HCl, Hg, SO_2, HF, and percentage of opacity, with the findings showing concentrations of 21.9 ± 0.86 mg/m^3, 13.7 ± 0.29 mg/m^3, 16.3 ± 0.57 mg/m^3, 0.022 ± 0.012 mg/m^3, 0.0069 ± 0.0014 mg/m^3, 5.6 ± 1.65 mg/m^3, 0.68 ± 0.17 mg/m^3, and 6.0 ± 0.96%, respectively. The amount of released pollutants of the O_3 system was evaluated for the levels of TSP, CO, NO_2, HCl, Hg, SO_2, HF, and percentage of opacity, with concentrations of 3.4 ± 0.13 mg/m^3, 1.7 ± 0.28 mg/m^3, 2.0 ± 0.39 mg/m^3, 0.015 ± 0.003 mg/m^3, 0.001 ± 0.0004 mg/m^3, 3.4 ± 0.2 mg/m^3, 0.013 ± 0.01 mg/m^3, and 5.0 ± 0.53%, respectively. It was found that, when compared with the U.S. EPA standards [32] for TSP, CO, NO_2, HCl, Hg, SO_2, HF, and percentage of opacity, the recommended safety thresholds were met or exceeded the expectations in reductions, with concentrations of 120 mg/m^3, 45.80 mg/m^3, 470 mg/m^3, 119 mg/m^3, 0.05 mg/m^3, 79 mg/m^3, 16.40 mg/m^3, and 10%, respectively.

Table 6. A comparison with the standard value of the pollution concentration released after combustion in a rotary kiln incinerator with and without an add-on O_3 generator (mg/m^3) and the standards of the U.S. EPA [31].

Parameters	Non-Ozone	Ozone	U.S. EPA [(1)] STD [31]
TSP (mg/m^3)	21.9 ± 0.86	3.4 ± 0.13	120
CO (mg/m^3)	13.7 ± 0.29	1.7 ± 0.28	45.80
NO_2 (mg/m^3)	16.3 ± 0.57	2.0 ± 0.39	470
HCl (mg/m^3)	0.022 ± 0.012	0.015 ± 0.003	119
Hg (mg/m^3)	0.0069 ± 0.0014	0.001 ± 0.0004	0.05
SO_2 (mg/m^3)	5.6 ± 1.65	3.4 ± 0.2	79
HF (mg/m^3)	0.68 ± 0.17	0.013 ± 0.01	16.40
Opacity (%)	6.0 ± 0.96	5.0 ± 0.53	10

Note: [(1)] The standards for controlling the emissions of pollutants released from an infectious waste incinerator in accordance with the methods prescribed by the United States Environmental Protection Agency (U.S. EPA), burning less than 50 tons/day. Remark: 15% oxygen content.

3.3. Efficiency Comparison of Wastewater with and without an O_3 System and the Standards of the U.S. EPA (1986)

The effluent samples released from the infectious waste incinerator in this study were collected at a sample volume equal to 5 L. The appearance of the effluent was light yellow. Laboratory tests were carried out against the Notification of the Ministry of Industry for the industrial effluent standard. The results of the analysis of the wastewater quality from the incineration of infectious waste were not found to exceed the standard. Ozone has been widely used for a long time, and now it is mixed with water in the tank before being injected into flue gas in the wet scrubber room. A chiller was installed in order to control the temperature of the cold water in the wet scrubber room during treatment, as it was found to be most efficient in the process of ozone gas oxidation. Ozone is a strong gas phase oxidant that can achieve pre-oxidation at low temperatures of 15–20 °C, which was a significant factor for this investigation [7,8]. This was followed by post-absorption to completely remove the oxidized products. Ozone has long been suggested as an alternative to improve air pollution and water quality [31]. A spray wet scrubber was installed to absorb SO_2 and other acidic pollutants effectively. To satisfy the increasingly stringent emission standards, some adjustments to the treatment methods must be made regularly, including mechanical add-ons, activated carbon injection to adsorb heavy metals and organic pollutants, a wet scrubbing tower, and ultra-fine atomization through venturi pump technology to further eliminate SO_2 and PM2.5 [33]. Finally, an end-of-pipe treatment device will again be added to further remove mercury, SO_3, sulfuric acid, aerosols, and PM2.5 among other pollutants to satisfy the expected arrival of even stricter emission standards [8,34,35]. The catalytic mechanism of ozone deep oxidation into gaseous pollutants was also proposed. In short, the reaction rate of gaseous pollutants to ozone, the key rate-determined step, will be accelerated by more active oxygen radicals with the help of ozone decomposition acceleration by metal ion valance cycles. The reactants' adsorption is the initial steps. It has been confirmed that the presence of ozone enhances the catalyst adsorption capacity [8], the dominant adsorbed form of nitrogen oxides on the catalyst surface. With the increasing valance of nitrogen oxides, the adsorption capacity was improved, and it significantly increased [8]. The concentration and emission of CO decreases with the increasing ratio of the ozone concentration in air, and the process is enhanced when the thermal power of the third combustion chamber is enlarged [36,37]. To ensure safe and robust treatment, it is vital to define the ozone demand and ozone kinetics to avoid as much variety in the outcomes as possible. The residual ozone will be separated into 2 parts. The first part will be fed to a dry ozone chamber which is located beyond a wet scrubber room. The second part will be mixed with water in a tank then the mixed ozone will be fed to a wet scrubber room in order to treat exhaust gas in a wet scrubber room. After the treatment, the mixed ozone will flow out to a pond and it will be used in the treatment system repeatedly. This is called a recirculation system. Experiments were performed to investigate the ozone kinetics and demand and to evaluate the effects on the air and water quality of the treatment systems [38]. In particular, the water quality parameters were measured, and the organic compound concentration changes during ozonation in the wet scrubber room were monitored and recorded [39]. The ozone reactions were described through kinetics, as they provided a better understanding of the ozone decay mechanisms, particularly the speciation forms of Cd, Pb, and Hg in the exhaust gas, that could be used to define further safe ozone treatment margins in the next steps [25,40]. It has also been found that the fluorescence of ozone could be used as a monitoring tool to control ozone [41]. These results were consistent with those of a previous study of combined adsorption via the O_3 oxidation process, so this appears to be superior technology for removing pollution from the contaminant air stream [7]. Thus, waste management with a rotary kiln system will enable meaningful improvement in the vital process of pollution elimination. However, further review of [8] has found that there was no refrigeration system in the controlling flue gas treatment room because it would cause the ozone to be insufficient for oxidation to treat the polluted gases, as the temperature was higher than 25 °C and would cause the ozone to decompose [7]. There was also no dry ozone system to treat it again before it was released into the atmosphere. Finally, this method may cause a cost increase with the installation of a treatment system.

4. Conclusions

This study found that significant levels of pollutant gases released from rotary kiln incinerators were lowered when they were fitted with a three-burner system. The design and installation methods also play a considerable role when it comes to efficiency in the combustion of infectious waste and reductions in toxic exhaust gases. Most notably, our research found that an add-on O_3 generator utilizing ozone oxidation technology was extremely efficient and effective in flue gas pollutant treatment, including at low temperatures of 15–20 °C in the scrubbing room, and led to emission readings much lower than the defined emission standards. Therefore, it was concluded that the use of an O_3 generator in a rotary kiln incinerator with a three-burner system considerably reduces combustion pollutants and also improves air quality, ultimately resulting in environmental improvements by mitigating the implications arising from the disposal of infectious waste. Finally, the overall conclusion is that employing multiple simultaneous removal techniques targeting a wide variety of multi-pollutants delivered the best results. Further studies are necessary to analyze the quality of the water for use in circulating systems for wastewater treatment or for the monitoring of further use in agriculture.

Author Contributions: Conceptualization, K.K., W.V., S.S., J.S., U.T. and B.B.; Formal analysis, K.K., W.V., S.S., J.S. and U.T.; Methodology, K.K. and W.V.; Writing—original draft, K.K. and W.V.; Writing—review and editing, K.K., W.V., S.S., J.S. and U.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was provided with financial support and technical support by Energy Experts Thailand Co., Ltd.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. The Statistic of Solid Waste. Available online: https://www.pcd.go.th/garbage/ (accessed on 20 November 2019).
2. Xu, X.-F.; Tan, Q.-Y.; Liu, L.-L.; Li, J.-H. Assessment of Medical Waste Disposal Technologies Based on the AHP. *Huan Jing Ke Xue* **2018**, *39*, 5717–5722.
3. Zhan, M.-X.; Chen, T.; Fu, J.-Y.; Lin, X.-Q.; Lu, S.-Y.; Li, X.-D.; Yan, J.-H.; Buekens, A. High temperature suppression of dioxins. *Chemosphere* **2016**, *146*, 182–188. [CrossRef]
4. Qian, L.; Chun, T.; Long, H.; Li, J.; Di, Z.; Meng, Q.; Wang, P. Emission reduction research and development of PCDD/Fs in the iron ore sintering. *Process Saf. Environ. Prot.* **2018**, *117*, 82–91. [CrossRef]
5. Zhang, M.; Buekens, A.; Li, X. Open burning as a source of dioxins. *Crit. Rev. Environ. Sci. Technol.* **2017**, *47*, 543–620. [CrossRef]
6. Rathoure, A. Dioxins source origin and toxicity assessment. *Biodivers. Int. J.* **2018**, *2*, 310–314. [CrossRef]
7. Swetha, G.; Gopi, T.; Chandra Shekar, S.; Ramakrishna, C.; Saini, B.; Rao, P.V.L. Combination of adsorption followed by ozone oxidation with pressure swing adsorption technology for the removal of VOCs from contaminated air streams. *Chem. Eng. Res. Des.* **2017**, *117*, 725–732. [CrossRef]
8. Lin, F.; Wang, Z.; Zhang, Z.; He, Y.; Zhu, Y.; Shao, J.; Yuan, D.; Chen, G.; Cen, K. Flue gas treatment with ozone oxidation: An overview on NOx, organic pollutants, and mercury. *Chem. Eng. J.* **2020**, *382*, 123030. [CrossRef]
9. Singh, S.; Prakash, V. Toxic environmental releases from medical waste incineration: A review. *Environ. Monit. Assess.* **2007**, *132*, 67–81. [CrossRef]
10. Hossain, M.S.; Santhanam, A.; Norulaini, N.N.; Omar, A.M. Clinical solid waste management practices and its impact on human health and environment–A review. *Waste Manag.* **2011**, *31*, 754–766. [CrossRef]
11. Hospital, Medical, and Infectious Waste Incinerators (HMIWI) Fact Sheets. Available online: https://www.epa.gov/stationary-sources-air-pollution/hospital-medical-and-infectious-waste-incinerators-hmiwi-fact (accessed on 20 November 2019).
12. Abd El-Salam, M.M. Hospital waste management in El-Beheira governorate, Egypt. *J. Environ. Manag.* **2010**, *91*, 618–629. [CrossRef] [PubMed]
13. Infection Waste Management Data. Available online: https://www.pcd.go.th/hazards/ (accessed on 20 November 2019).
14. Langlais, B.; Reckhow, D.A.; Brink, D.R. *Ozone in Water Treatment: Application and Engineering*; Lewis Publishers: Chelsea, MI, USA, 1991.
15. Wongsadee, T.; Trachoo, N.; Suttajit, M. Effects of ozone on the survival of Campylobacter jejuni (Thai). *Asia-Pac. J. Sci. Technol.* **2008**, *13*, 919–929.
16. Dufresne, S.; Hewitt, A.; Robitaille, S. Ozone sterilization: Another option for healthcare in the 21st century. *Am. J. Infect. Control* **2004**, *32*, E26–E27. [CrossRef]
17. Silva, L.M.d.; Jardim, W.F. Trends and strategies of ozone application in environmental problems. *Química Nova* **2006**, *29*, 310–317. [CrossRef]
18. Tichonovas, M.; Krugly, E.; Jankunaite, D.; Racys, V.; Martuzevicius, D. Ozone-UV-catalysis based advanced oxidation process for wastewater treatment. *Environ. Sci. Pollut. Res.* **2017**, *24*, 17584–17597. [CrossRef]
19. Cuerda-Correa, E.M.; Alexandre-Franco, M.F.; Fernández-González, C. Advanced oxidation processes for the removal of antibiotics from water. An overview. *Water* **2020**, *12*, 102. [CrossRef]
20. Nabity, J.A.; Lee, J.M. Low temperature ozone oxidation of solid waste surrogates. *Adv. Space Res.* **2015**, *56*, 970–981. [CrossRef]
21. Scandelai, A.P.J.; Filho, L.C.; Martins, D.C.C.; Freitas, T.K.F.D.S.; Garcia, J.C.; Tavares, C.R.G. Combined processes of ozonation and supercritical water oxidation for landfill leachate degradation. *Waste Manag.* **2018**, *77*, 466–476. [CrossRef]
22. Nidoni, P.G. Incineration process for solid waste management and effective utilization of by products. *Int. Res. J. Eng. Technol.* **2017**, *4*, 378–382.
23. Gupta, G.K.; Liu, H.; Shukla, P. Pulp and paper industry–based pollutants, their health hazards and environmental risks. *Curr. Opin. Environ. Sci. Health* **2019**, *12*, 48–56.
24. Jiang, X.; Li, Y.; Yan, J. Hazardous waste incineration in a rotary kiln: A review. *Waste Dispos. Sustain. Energy.* **2019**, *1*, 3–37. [CrossRef]
25. O'Connor, D.; Hou, D.; Ok, Y.S.; Mulder, J.; Duan, L.; Wu, Q.; Wang, S.; Tack, F.M.G.; Rinklebe, J. Mercury speciation, transformation, and transportation in soils, atmospheric flux, and implications for risk management: A critical review. *Environ. Int.* **2019**, *126*, 747–761. [CrossRef]
26. Lombardi, F.; Lategano, E.; Cordiner, S.; Torretta, V. Waste incineration in rotary kilns: A new simulation combustion tool to support design and technical change. *Waste Manag. Res.* **2013**, *31*, 739–750. [CrossRef]
27. Vattanapuripakorn, W.; Khannam, K.; Sonsupap, S.; Tongsantia, U.; Sarasamkan, J.; Bubphachot, B. Treatment of Flue Gas from an Infectious Waste Incinerator using the Ozone System ARTICLE INFO ABSTRACT. *Environ. Nat. Resour. J.* **2021**, *19*, 348–357. [CrossRef]
28. Ngessa, V. A study of basic costs for tracking total cost of ownership of information and communication technology in an academic institution: The case of the institute of accountancy arusha. *Int. J. Adv. Res.* **2019**, *7*, 228–234. [CrossRef]
29. Wei, C.; Zhang, F.; Hu, Y.; Feng, C.; Wu, H. Ozonation in water treatment: The generation, basic properties of ozone and its practical application. *Rev. Chem. Eng.* **2017**, *33*, 49–89. [CrossRef]
30. Oleniacz, R. Impact of a large medical waste incinerator on air quality. *Pol. J. Environ. Stud. Ser. Monogr. (Eds J. Bień L. Woln.)* **2010**, *2*, 176–182.

31. Nitrogen Oxides (NOx): Why and How They Are Controlled; EPA-456/F-99-006R. Available online: https://www3.epa.gov/ttn/catc/cica/other7_e.html (accessed on 20 November 2019).
32. National air quality and emissions trends report. Available online: https://www.epa.gov/sites/default/files/2017-11/documents/trends_report_1999.pdf (accessed on 20 November 2019).
33. Wu, H.; Wang, Q.; Yang, H. Promoting the Removal of Particulate Matter by Heterogeneous Vapor Condensation in a Double-Loop Wet Flue Gas Desulfurization System. *Energy Fuels* **2019**, *33*, 4632–4639. [CrossRef]
34. Sarbassov, Y.; Duan, L.; Manovic, V.; Anthony, E.J. Sulfur trioxide formation/emissions in coal-fired air- and oxy-fuel combustion processes: A review. *Greenh. Gases Sci. Technol.* **2018**, *8*, 402–428. [CrossRef]
35. Anderlohr, C.; Brachert, L.; Mertens, J.; Schaber, K. Collection and Generation of Sulfuric Acid Aerosols in a Wet Electrostatic Precipitator. *Aerosol Sci. Technol.* **2015**, *49*, 144–151. [CrossRef]
36. Simone, D. The Production and Characterisation of High Purity Ozone and Experimental and Modelling Studies of Anomalous Oxygen Isotope Effects in the Formation of Carbon Dioxide from Irradiated Mixtures of Carbon Monoxide and Ozone or Oxygen. Ph.D. Thesis, Université Pierre et Marie Curie, lle de France, Paris, France, July 2014.
37. Magdziarz, A.; Wilk, M. Ozone Effects on the Emissions of Pollutants Coming from Natural Gas Combustion. *Pol. J. Environ. Stud.* **2010**, *19*, 1331–1336.
38. Review of Literature to Determine the Uses for Ozone in the Treatment of Water and Wastewater. Available online: https://www.crew.ac.uk/publication/uses-ozone-treatment-water-and-wastewater (accessed on 24 September 2021).
39. Tozihi, M.; Vahedpour, M.; Nazari, F.A. Theoretical Study on the Mechanism and Thermodynamics of Ozone-Water Gas Phase Reaction. *J. Iran. Chem. Soc.* **2010**, *7*, 585–596. [CrossRef]
40. Ozon som Alternativ for Behandling av Ballastvann. Available online: https://hdl.handle.net/11250/2657574 (accessed on 21 November 2019).
41. Spiliotopoulou, A.; Rojas-Tirado, P.; Chhetri, R.K.; Kaarsholm, K.M.S.; Martin, R.; Pedersen, P.B.; Pedersen, L.-F.; Andersen, H.R. Ozonation control and effects of ozone on water quality in recirculating aquaculture systems. *Water Res.* **2018**, *133*, 289–298. [CrossRef] [PubMed]