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In-situ disinfection of wastes generated in dwellings by utilizing ozone for their safe incorporation into the recycling chain

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ABSTRACT

The Covid-19 pandemic has certainly changed behaviour patterns in many aspects of life, such as the management of solid wastes inside residential spaces. The **goal** of this research work is to study an ozone generator device as a disinfection and sterilization tool for these wastes in dwellings themselves, thus re-establishing the selective collection to take them back to the recycling chain. In addition, an approach to the risk verification is made. The **methodology** is based on an experimentation with a device designed to be as cheap as possible. A room like a bedroom is used as a test bed to apply the device, but with no people inside the room to avoid risks. The **results** show that the device is feasible, **concluding** that risks are acceptable if its use is correct and appropriate equipment is available to be applied and controlled, all without prejudice of the rigorous control by the competent authorities that approve its use.

1. Introduction

The emergence and expansion of Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) has significantly affected the management of urban solid wastes (Kulkarni and Anantharama, 2020). An aspect that has arisen interest is the possibility of the virus propagation through solid wastes (Mol and Caldas, 2020), and particularly the risk of manipulating them as it is possible to become infected by direct contact, e.g., touching a contaminated element and then touching mouth, nose or eyes. For this reason, attention was first paid to the persistence of the active virus in surfaces. This aspect has been widely analysed by important studies (Aboubakr et al., 2020; Aydogdu, 2021; Carraturo, 2020; Kampf et al., 2020; Marquès and Domingo, 2021) that stated that human coronaviruses, such as Severe Acute Respiratory Syndrome (SARS), Middle East Respiratory Syndrome (MERS) and COVID-19, could persist in inanimate surface for short or longer periods of time according to both the type of material and the environmental conditions (Chan et al., 2020). For instance, van Doremalen et al. (2020) detected the virus up to 3 h after aerosolization, up to 4 h in copper, up to 24 h in cardboard, and between 2 and 3 days in plastic and stainless steel. As a result, and considering that the interior of dwellings is an environment with the greatest transmission rate (Marín-García et al., 2020), several researchers, experts and teamworks (Cervantes et al., 2021; Haque et al., 2020; Sharma et al., 2020; di Lavoro, 2021; International solid waste Association ISWA, 2020) have focused their studies on establishing guidelines for waste management, such as the guidelines on users' behaviour in dwellings where there are sick people or people in quarantine because of COVID-19. The common goal of these guidelines is to avoid these two situations (Di Maria et al., 2020): (i) The contact with contaminated surfaces and objects when manipulating or using wastes. (ii) The generation of aerosol when manipulating, packing, or unpacking.

Considering these two aspects and the indications by researchers, experts and teamworks previously mentioned, the domestic wastes most capable of being contaminated (Waste with Covid Risk in Households (WCRH)), i.e., those related to sick people or people in quarantine, or even the person looking after them, should be manipulated following certain protocols that include interrupting the shipment of WCRH to the recycling circuit. Regarding the guidelines developed by international and national institutions and authorities (Penteado and de Castro, 2021), Table 1 includes a list of the guidelines developed by 12 institutions and countries.

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As mentioned above, these guidelines, which were published in the first months of the pandemic, are based on the belief that the presence of virus in the various surfaces is a route of transmission. However, the state of science has evolved, and questions (Goldman, 2020; Mondelli et al., 2020) on the effectiveness and the time of transmission by surface contact have raised, considering that the risk is lower than that first thought (Harvey et al., 2020).

However, risk exists. Guidelines do not recommend the selective domestic recycling of these wastes, so this aspect should be analysed to know if it is possible to apply techniques that allow the selective recycling to be carried out under such circumstances by using a safe and low-cost device.

2. Methodology

First, information was compiled about the requirements that technologies should fulfil. Based on this information, the technique or technology was selected, justifying the reason of the choice, and finally, the experimental stage began. The most appropriate device was designed and created in this stage, and then tested in a controlled environment.

The results obtained were analysed and discussed. Finally, conclusions were drawn.

2.1. Selection of the technique

The goal is that recyclable wastes are safe to be separated according to the type and material (mainly plastic containers; paper and cardboard containers; glass; etc.), so the following requirements should be fulfilled: (i) Effective deactivation of possible pathogens, such as viruses (virucides), with no risk for people. (ii) Use of dustbins to deposit the wastes to be used without the need that the sick or potentially sick person is in contact with them, i.e., dustbins should have an operation and use system with automatic opening and closure or with a manual opening and closure through a pedal.

In a preliminary search with the techniques (Ronconi, 2020) based on keywords and references, many methods based on chemical substances (ozone, sodium hypochlorite or bleach, hydrogen peroxide (H_2O_2), alcohol, chlorine dioxide, soaps, ethylene oxide, etc.) or on physical processes (UV radiation, gamma radiation, microwaves, heat, etc.) were detected. Taking into account that it is about applying these disinfections in dwellings, the ideal method to choose should be inexpensive, safe, fast-acting, and provide a high level of virus removal without leaving harmful residues or end products or by-products. In this sense, the aforementioned chemical substances in their liquid state are not very practical and operative to continuously disinfect all waste destined for possible recycling in dwellings, since it is difficult to guarantee the adequate and economic impregnation of said waste. On the other hand, the use of ionizing radiation or high temperatures that guarantee disinfection is often problematic given the complexity of the security measures and the equipment necessary to apply them.

For this reason, the options applicable in this work for dwellings are ozone and UV radiation. Both should fulfil the requirements established in the regulation of each country. As a result of the emergence of SARS-CoV-2, several governmental documents related to the ozone (Government of Spain. Ministry of Labor and Social Economy, 2020; Ministry of Health, 2020a) and to the application of UVA radiation (Ministry of Health. Government of Spain, 2020b) have been published.

Although the viricidal capacity of the UV radiation has been studied (Heilingloh et al., 2020), it has several disadvantages (de Andrés Miguel et al., 2020) related to its practical application to the case study: (i) Among the types of UV radiation that could be used according to the interval of wavelength (Type A, B, C, and far C), the C and far C are those with the capacity of inactivating both infectious pathogens and bacteria and viruses; however, they could be harmful for people exposed to them. (ii) The direct impact of the UV radiation on a surface could inactivate

Table 1
Guidelines found in 12 institutions and countries on the management of solid wastes generated by patients with Covid-19 or in quarantine inside dwellings.

	Institutions and countries										
Guidelines detected	WHO	ISWA	BC	EC	US	UK	FRA	GER	ITA	POR	SP
To separate the WCRH from the rest of wastes	x	x	x	x	x	x	x	x	x	x	x
To stop sending the WCRH to the recycling circuit	x	x	x	x	x	x	x	x	x	x	x
To pack the WCRH appropriately and safely	x	x	x	x	x	x	x	x	x	x	x
To keep the WCRH for some time		x			x	72 h	24 h	x*			
Dustbin to deposit the WCRH in the room				x			x			x	x
Pedal dustbin to deposit the WCRH				x						x	x
Wastes of carers separately				x							x
Appropriate closure of bags for WCRH (hermetic)				x	x	x	x	x	x	x	x
Mention to disposable bags						x	x				
To put the bag with WCRH in a second bag				x		x	x	x	x	x	x
To put the wastes of the carer in a second bag									x	x	x
To put the second bag with WCRH in a third bag									x	x	x
Resistant bag				x	x	x	x	x	x	x	x
Mention to liquid wastes separately								x			
Sharp objects protected				x	x	x	x	x	x	x	x
To keep bags in a non-accessible place								x			
To not comprise bags									x	x	x
Mention to not filling the bag with WCRH										x	

Reference	**Scope**
WHO (World Health Organization) (WHO, 2020)	International
ISWA (International Solid Waste Association) (Scheinberg et al., 2020) (Penteado and de Castro, 2021)	International
BC (Basel Convention) (Basel Convention, 2021; Penteado and de Castro, 2021)	International
EC (European Commission) (European Commission, 2020; Penteado and de Castro, 2021)	Regional
US (United States Environmental Protection Agency (USEPA)) (Agency, 2020; Penteado and de Castro, 2021)	National
UK (United Kingdom) (Government of the United kingdom, 2020a; Government of the United kingdom, 2020b)	National
FRA (France) (Ministère des Solidarités et de la Santé. République Française, 2020)	National
GER (Germany) (Ministerium für Umwelt, 2020)	National
ITA (Italy) (di Lavoro, 2021)	National
POR (Portugal) (Agência Portuguesa de Ambiente, 2020; Direção-Geral da Saúde, 2020)	National
SP (Spain) (Ministry of Health. Government of Spain, 2020; Government of Spain, 2020)	National

*In Germany, some recyclable elements or destined for the recycling facility will be kept depositing them in an appropriate place once the quarantine is over.

all the microorganisms, so it would not be effective in shade zones or in the zones covered by an opaque layer. (iii) The required application times could vary from 6 min to several hours according to many factors, such as the distance of the emitter to the surface to be treated, the power, the reflectivity of surfaces, etc.

The recent review by Bayarri et al., 2021 confirmed the effectiveness of applying the ozone gas to deactivate SARS-CoV-2, as well as other viruses and pathogens. For instance, face masks were disinfected (Lee et al., 2020) by using the ozone produced by a dielectric barrier discharge plasma generator for 1 min, and ozone was applied to food (Quevedo-León et al., 2020) in doses between 10 and 20 ppm for some minutes (from 10 to 15 min).

One of the most interesting studies from the practical point of view and related to the goal of this paper is that by Dennis et al., 2020. This study described direct measurements of ozone concentration that could be reached in small and enclosed containers (plastic storage boxes) used as improvised decontamination systems for small items, e.g., disposable personal protective equipment (N95 masks, nitrile gloves, etc.), clothing, small packages, and food. This study also analysed the doses and times required to destroy the virus, mentioning many authors (Farooq and Akhlaque, 1983; Hudson et al., 2009; Li and Wang, 2003; Rojas-Valencia, 2011; Tseng and Li, 2006, 2008; Zhang et al., 2004; Gray, 2013).

Therefore, the methodology used is based on said experiences and reported results on disinfection of different types of virions, as well as recent studies in which Covid-19 is already mentioned, such as the review carried out by Lin et al. (2020) on various disinfection techniques and technologies or others more specific on ozone such as Bayarri et al., 2021, or Tseng and Li (2008) among others, in which it is specified that although there are various factors that can vary the effectiveness of disinfection (humidity, temperature, homogeneity of concentration, impregnation or contact with surfaces and level of the concentration of disinfectant, type, texture and geometry of material, etc.) and that should be studied in each case, they also conclude that an ozone concentration in the environment as applied during this experiment, as well as the exposure time taken as a reference, are sufficient to achieve virus deactivation at levels higher than 90% and even close to 100%.

The study (Dennis et al., 2020) concluded that a 55% relative humidity and an ozone concentration of 10 ppm for approximately 12 min (113.59 min [ppm]) are enough to reduce both the virus by 99% in surfaces and air and other microorganisms mentioned in literature by 80%. In addition, at 45% relative humidity, a dose of 20 ppm for 15 min (300 min [ppm]) is a practical dose that could inactive more than 99% of virions in many solid surfaces. However, if relative humidity increases from 55% to 85% with approximately half the ozone dose, similar results are obtained (Government of Spain. Ministry of Labor and Social Economy, 2020).

Despite its effectiveness, the ozone gas could lead to risks, including those related to human health, so limitations related to the exposure degree, use, commercialization, proximity to inflammable substances and ignition sources, among others, are established (Government of Spain. Ministry of Labor and Social Economy, 2020). For instance, Quevedo-León et al. (2020) indicated that exposure to human should be limited to 0.05 ppm for 8hr. Moreover, the WHO (WHO, n.d.) provided a guideline value of 100 μg/m^3 (0.10 mg/m^3 – 0.051 ppm) as the maximum 8 h mean ozone concentration. On the other hand, in Europe (European Commission, 2003), an average maximum concentration of 120 μg/m^3 (0.12 mg/m^3 – 0.061 ppm) is not allowed for 8 h nor 240 μg/m^3 (0.24 mg/m^3 – 0.122 ppm) for 1 h. However, in USA, the OSHA (Occupational Safety and Health Administration) website cites several ACGIH (American Conference of Governmental Industrial Hygienists) guidelines for ozone in the workplace (OSHA, n.d.): (i) 0.2 ppm for no more than 2 h exposure. (ii) 0.1, 0.08, and 0.05 ppm for 8 h per day exposure doing light, moderate or heavy work, respectively.

On the other hand, the National Institute of Occupational Safety and Health (NIOSH), a United States federal agency, recommends that the limit of 0.1 ppm should not be exceeded (Centers for Disease Control and Prevention CDC, 2021), making an interesting exposition of Immediately Dangerous to Life or Health Concentrations (IDLH) (Centers for Disease Control and Prevention CDC, 2021). The United States Environmental Protection Agency (EPA) establishes an average maximum concentration of 0.08 ppm for 8 h in the open air.

To detect risks, this paper therefore uses the ozone concentrations greater than 0.05 ppm (although it could vary according to the exposure time) that are produced in the experiment room. The goal is to verify if there is risk when applying ozone inside dustbins used to separate wastes, which are then recycled.

2.2. Experimentation with the technique selected: ozone

The experimentation consisted in creating a device or prototype made up of several recyclable waste bins connected to an ozone generator. Once the waste bins were full and hermetically closed, the ozone generator was activated for disinfection. In this process, the ozone level inside and outside bins was recorded with sensors to verify if the ozone concentration was high (10 ppm for approximately 12 min) and lasted enough inside them to disinfect appropriately. On the other hand, the ozone levels reached outside were simultaneously recorded, verifying if they were low enough to not be dangerous for people in the room.

2.3. Device or prototype used for the experimentation with ozone

The device or prototype used for the experimentation (Fig. 1) was an ozone generator connected to three waste bins through polypropylene corrugated tubes, with a diameter of 110 mm. Moreover, each tube could cut the supply independently, which was activated when desired or when a certain ozone concentration was detected inside the bins. On the other hand, the ozone generator was also connected with the exterior through a window of the experiment room by using another tube with the same diameter, thus ventilating the generator, and extracting, when required, the ozone of the waste bins through an integrated and motorized fan. Furthermore, non-return valves were available to avoid that ozone escapes when was introduced in the bins. Ozone could also be extracted in a safe way by activating and deactivating these devices, or through the reversing of the non-return effect.

The ozone concentration was measured in both the environment of the experiment room and inside the waste bins. A low concentration sensor was used to measure the ozone in the environment of the experiment room and was placed close to the device or prototype because it was the most critical place as greater concentrations were there in case of leaks. On the other hand, a high concentration sensor was placed inside the waste bin. Fans were also placed inside them to ensure that the ozone was mixed in a uniform way. Measurements were conducted in Seville (Spain) between 26 March and 6 April 2021, recording a temperature and relative humidity inside the experiment room between 20 and 24 °C and between 52 and 61 %, respectively, measured with a DHT22 sensor for Arduino. The room was closed during measurements, so air renovations were virtually null as the goal was to simulate the most unfavourable case. The ozone level outside the building was also measured to detect and compare the accuracies of the low- and high-cost sensors available.

Although the study could have been extended in time to find out possible long-term implications for human health, due to the results obtained in terms of the absence of dangerous concentrations and the effective elimination of ozone by the proposed method if the procedures are followed adequate, it is understood that in principle it is not necessary to expand such studies, although they may be the subject of another future investigation.

2.4. Characteristics of the experiment room with ozone

An empty room with a door and a window to the exterior was used as

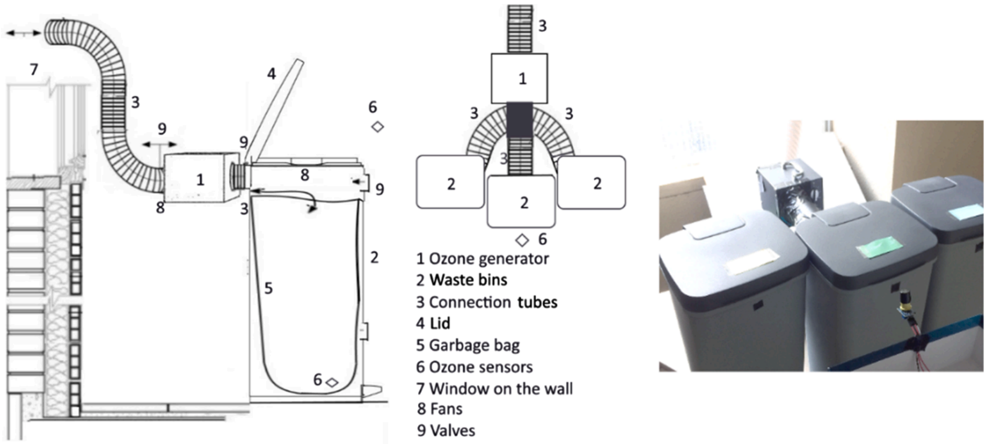


Fig. 1. Device or prototype used for the experimentation.

a test bed; this room was always empty for safe reasons. All tests were performed in this room by using an ozone generator. This room was selected as it is like a small bedroom, usual in dwellings, so it was the most unfavourable case where a person could be confined during the days recommended according to the criteria by WHO (2020). Therefore, the room chosen was the adequate for the objective sought since, due to its characteristics, it adjusts in terms of the most common minimum hygienic and sanitary standards in Europe (Appolloni et al., 2020), especially in terms of dimensions, ventilation and volume, and so, the experimentation was carried out on the most unfavorable case, which allows the results to be on the safety side and thereupon, within the objective pursued. The characteristics of the experiment room are shown in Fig. 2.

For the experimentation, ozone concentrations were up to 30 ppm inside waste bins. The reason was to avoid risks in case of leaks. The volume of the experiment room was approximately 25 m^3, and at a temperature like that recorded (between 20 and 24 °C), 1 ppm was equivalent to 1.96 mg/m^3 (molecular weight of the 48 ozone). Based on these data, if there was an accidental leak in the three waste bins at the same time and concentrations of 30 ppm were reached in each waste bin of 20 L (0.02 m^3), theoretically 1.96x30x3x0.02 = 3.528 mg of ozone would escape, and spread in the volume of the room it would imply a concentration of 3.528/25 = 0.141 mg/m^3 (i.e., 0.07 ppm), thus exceeding the referential limit established (0.05 ppm) to detect risk for people. Nevertheless, this value could be accepted as long as the exposure time recommended is not exceeded (Centers for Disease Control and Prevention CDC, 2021; European Commission, 2003; OSHA, n.d.; Quevedo-León et al., 2020; WHO, n.d.). Greater concentrations could be injected in the waste bins, particularly if the volume of the room were higher; however, this limit was established for this experimentation to guarantee safety.

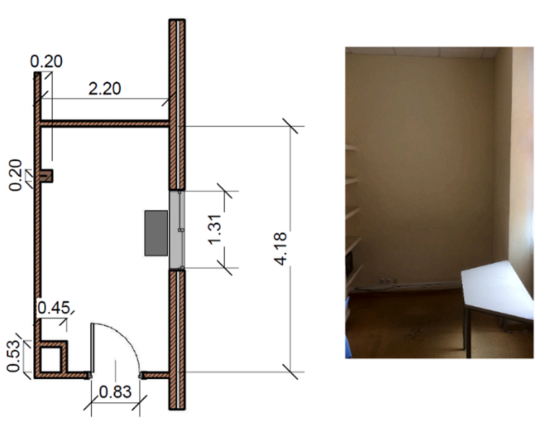


Fig. 2. Characteristics and dimensions in metres of the experiment room with ozone (approximate total volume = 25 m^3).

2.5. Ozone generator used

Although Dennis et al., 2020 indicated that an ozone generator that produces 600 mg/h of ozone could give good results, a low-cost commercial ozone generator easy to acquire (MO-5000-OZS) was used as several waste bins were simultaneously used (the goal was using a device as economic as possible). This is a high-performance generator, with a nominal ozone production rate (specified by the manufacturer) of 5000 mg/h, generally used to disinfect rooms. This generator has a timer (0–120 min). Moreover, this device is controlled (connection-disconnection) according to both the ozone levels and the needs detected by the sensors.

2.6. Sensors

Although sensors should not be used to detect risks, two low-cost sensors were used as the goal was that the devices used were affordable to almost everyone. One of the sensors had greater accuracy, sensitivity, and cost. The reliability of data obtained by the low-cost sensors were verified, particularly low concentrations in the environment of the experiment room. Table 2 includes the main characteristics of each sensor. The low-cost sensors, used with Arduino®, were MQ131 (low concentration) and CJMCU-131 (high concentration) and measured the ozone outside and inside the waste bins, respectively. Moreover, a more expensive OZAQ200® sensor was used to verify if the data obtained with MQ131 were reliable enough, particularly in relation to the ozone concentration in the environment as these data were related to the people's safety when using the device or prototype. Another high cost and accuracy sensor for high ozone concentration was not used inside the waste bins because the results obtained by CJMCU-131 were checked with the theoretical calculations specified below and because of the ozone production (mg/h) of the generator (Dennis et al., 2020). Fig. 3 shows MQ-131 and its position with the waste bins.

2.7. Experimentation waste bins for their decontamination with ozone

Waste bins (commercial dustbins) of 20 L of capacity, with dimensions of 30 × 29 × 43 cm were chosen. These bins are very economic, with a lid-opening pedal with an external mechanism, and their interior is compact and airtight. The lid is fully adjusted to the edge when closing the bin. However, rubber gaskets were included in the edges of the lids to improve the closure, looking for possible leak points and sealing them appropriately. Another advantage considered when

Table 2
Specifications of the sensors used.

Model	MQ131 * Low concentration	CJMCU-131 * High concentration	OZAQ200 Aeroqual Low concentration
Sensor Type	Semiconductor	Semiconductor	Semiconductor GSS
Standard Encapsulation	Plastic cap	Bakelite, Metal cap	–
Detection range	10–1000 ppb (Parts per billion) or 0.01–1 ppm (Parts per million)	10–1000 ppm	0–0.15 ppm
Response Time	Adjustable	Adjustable	60 s
Accuracy	**	**	Accuracy of Factory Calibration< ±0.005 ppm
Resolution	0.01 ppm	0.1 ppm	0.001 ppm
Temp	From −20 °C to 50 °C	From −20 °C to 50 °C	From 0 to 40 °C
Relative Humidity	From 15 to 95% (no condensation)	From 15 to 95% (no condensation)	From 10 to 90%
Approximate cost. Full equipment working (assembly included). March 2021	$162 + taxes	$209 + taxes	$950 + taxes (monitor + head sensor)
Software code and other instructions and adaptations followed	(Pueyo, 2020; Staquet, n.d.)		Included in the device

*Requires minimum 48 h preheat time before giving consistent results (also called "burn-in" time). Preheat Time: 3 min.
** The actual accuracy of these sensors depends on several internal and external factors (work temperature, humidity, sensor age, etc.). The accuracy will be therefore proved in their experimental application.

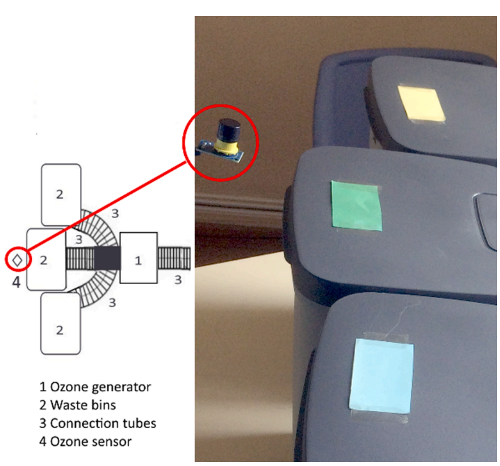


Fig. 3. Position of MQ-131 when data of the ozone level outside the waste bins were collected.

choosing the waste bins was their material (polypropylene) because it does not have an extinction effect on the ozone (Dennis et al., 2020). On the other hand, garbage bags were placed inside the bins to keep the wastes, and the inlet tube penetrated inside them easily due to both the height of the garbage bags and the position of the inlet tube itself. The colour of the garbage bags also corresponded to the type of waste, and their material was also semi-rigid polypropylene, thus making them lasting, waterproof, washable, reusable, and easy to wash. Their handles were also strong and resistant, useful to be moved.

According to the experimentation country (Spain) and not including bins for organic waste (grey or brown waste bins), a bin for glass waste (green), another for paper and cardboard waste (blue), and another for light containers (yellow) were used.

2.8. Elements to be disinfected, cycles, and wall effect

In the experimentation in the room with ozone, the waste bins were filled according to the studies related to this aspect (Estadísticas sobre el reciclaje de envases domésticos en España). The materials for each selective collection bin followed the same criteria previously mentioned, and the selection of types of waste focused on choosing the elements that are introduced most frequently in the different recycling bins used in dwellings. On the other hand, the waste load was considered in the understanding that it was a question of providing the maximum amount of material to simulate the most unfavorable situation. Regarding the effectiveness of the ozone level, it was considered adequate based on the aforementioned literature authors (Dennis et al., 2020; Farooq and Akhlaque, 1983; Hudson et al., 2009; Li and Wang, 2003; Rojas-Valencia, 2011; Tseng and Li, 2006, 2008; Zhang et al., 2004; Gray, 2013).

Regarding the waste with which the bins were filled, 500 ml plastic bottles of mineral water, two aluminum cans of 330 ml capacity and three boxes, all empty, were placed in the yellow bin. Paper and cardboard were placed in the blue bin (dirty napkins and tissues should be placed in the organic waste bin and follow the guidelines mentioned in Section 1). Finally, empty glass bottles were placed in the green 25 cl bin. To constitute the most unfavourable case, plastic containers were partially compressed, paper and cardboard were compressed to a size lower than 15x15 cm, and glass was partially fragmented.

When the bins were empty, they were not used in the experimentation. They were filled with ozone a dozen of previous cycles before filling them with the containers described to reduce as much as possible the wall effect (the reduction of the average life of the ozone due to its contact with a surface) that both surfaces and the fixed elements of the bins, including servo, fan, and sensors, could produce. As for the recyclable containers put in the bins, this effect produces that, in a first decontamination cycle, it takes more time to reach the ozone concentration desired, and the ozone disappears differently than in the following cycles.

2.9. Experimentation

In the first experiment, the generator that injected ozone to the three bins was activated, and when a bin reached a concentration of 30 ppm (the safety limit established), its supply was cut, but the other bins kept receiving ozone until reaching that concentration, and then the supply was also cut. The supply was cut by covering the input opening of the ozone by activating a SG90 mini servo motor for Arduino placed in each bin. When the servo was activated, the ozone input was closed by turning a door that sealed the tube mouth (Fig. 4A). In other words, the three bins theoretically received approximately 5000 mg/h (i.e., 1666 mg/h in each bin) (Fig. 4B). When a bin received 30 ppm, it stopped receiving ozone as the respective servo was activated (Fig. 4C). The other two bins received around 2500 mg/h until one of them reached 30 ppm, thus no receiving ozone as the following servo was activated (Fig. 4D), and the last bin received from that moment 5000 mg/h. When this bin also reached 30 ppm, the ozone generator stopped (Fig. 4E). The ozone levels were continuously recorded until they were virtually null. To guarantee valid results, several tests were performed by changing the position of the bins to prove that similar results were obtained, so the ozone volume was analogous.

The ozone levels in the environment of the experiment room were always detected by MQ131, with both the three bins hermetically closed

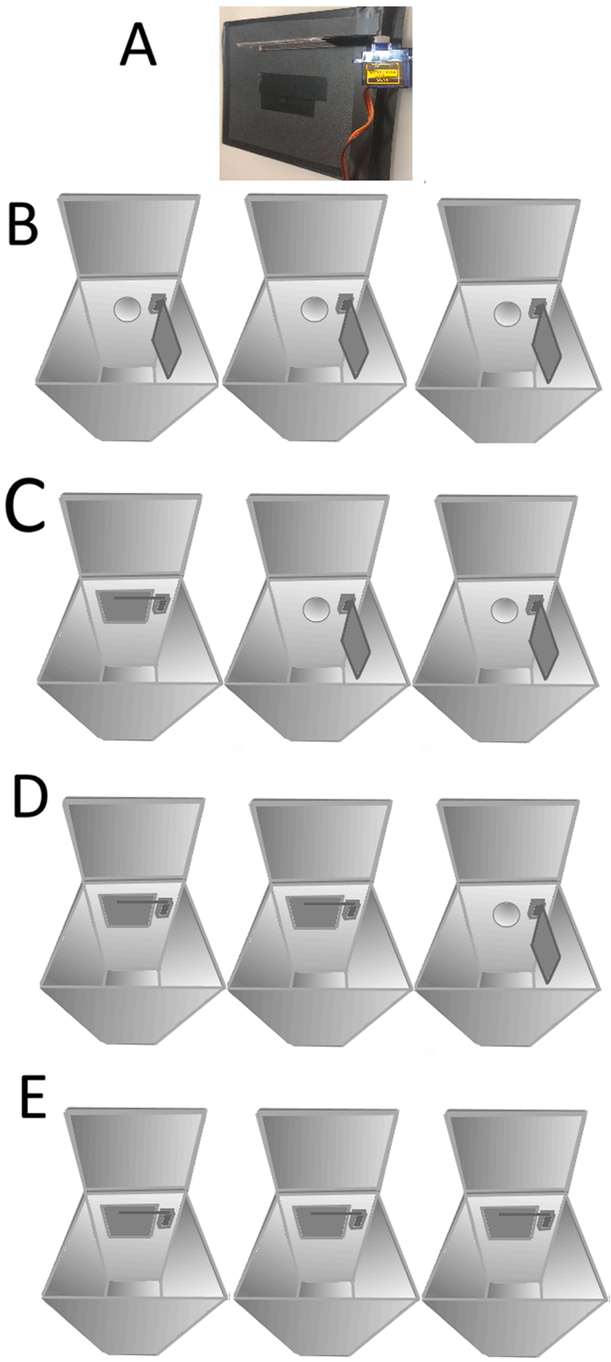


Fig. 4. A) Bins with the doors activated by the servo motor to control the ozone input; B) when no bin reached 30 ppm; C) when the first bin reached 30 ppm; D) when two bins reached 30 ppm; and E) when all bins reached 30 ppm.

and the window and the door of the room closed. This initial experiment was conducted in three subsequent times to simulate three decontamination cycles.

Moreover, environmental measurements were conducted to detect possible deviations between MQ131 and OZAQ200 Aeroqual.

2.10. Theoretical calculations

To verify theoretically both ozone concentration levels and the time required, the simplified calculation was carried out by applying Equations (1) and (2) according to Dennis et al., 2020.

$$C_{ppm} = \frac{t_a * R_{mg/hr}}{60*117.9*F*v_{m^3}} \tag{1}$$

$$t_a = 60*117.9*F\frac{C_{ppm}*v_{m^3}}{R_{mg/hr}} \tag{2}$$

where C_{ppm} is the ozone concentration reached, t_a is the time in seconds in which the ozone generator is operating, $R_{mg/hr}$ is the ozone rate produced by the generator, V is the volume in m^3 of the waste bin, F is a correction factor depending on possible leaks, delays, material cooling, rusting, etc., and 117.9 is the conversion factor from mg/m^3 to ppm and from hours to minutes.

Thus, with MO-5000-OZS and three bins of 20 L each (60 L in total), it is started from a $R_{mg/hr} = 5000$ for a $V = 0.06\ m^3$. If the bin is empty ($F = 10$) (Dennis et al., 2020) and the generator is working for 20 s, a theoretical C_{ppm} of 23.56 ppm is reached. On the other hand, if a concentration of 20 ppm is to be reached, considering a F of 50 (Dennis et al., 2020) that could be the coefficient for the bin full, the resulting theoretical t_a is 84.88 s.

Due to the existence of several influential factors and to the possibility of theoretical results of low reliability about the ozone decomposition over time, this study only verified the theoretical calculation of the maximum concentration reached. In other words, it was studied in an experimental way whether the ozone concentration was high enough and kept over time to effectively deactivate the pathogens at the temperature and humidity existing in the experimentation. On the other hand, the air inside the bin was moved by fans usually used to cool personal computers, and in the disinfection, no air passed in or out the bins.

3. Results

The results of the experimentation were used to verify whether the system proposed was appropriate for the goal established. The experiment in which the generator that injected ozone to the three bins full of wastes was activated aimed at verifying the time required to reach the ozone level of 30 ppm. Afterwards, when the ozone supply was cut, the goal was to know the time and way required to reduce the ozone concentration inside the bins, thus indicating to what extent the contact with the ozone of each type of waste contributed to its disappearance, and therefore, the exposure time required for its disinfection in each case. For this purpose, three cycles were carried out, i.e., the experiment was three times subsequently repeated. It was checked between cycles that there was no ozone inside the bins. Wastes were in the bins in all cycles without being altered or manipulated.

The results (Fig. 5) showed that the indications by Dennis et al., 2020 were fulfilled, and the materials with greater surface, porous or holding more dust were usually the materials requiring more time, particularly to reach the ozone level required. This did not take place in the second and third cycles in which the extinction effect of the ozone was significantly reduced, and most wastes had similar time to reach the concentration required.

Fig. 5 shows that the green bin with glass first reached 30 ppm (around 4 min) in the first cycle, and then the yellow container with slight plastic containers, cans, and carton (a little over 5 min). The blue with paper and cardboard was the last reaching 30 ppm: due to the supply cut of the other bins when reaching 30 ppm, from 4 min upwards its progression was speeded up until reaching 30 ppm after a little over 8 min. As mentioned above, these differences were mainly due to the type of material stored and its surfaces, which were related to the effect wall and to the internal volume with and without wastes, among others. On the other hand, with an F between 10 and 50 and according to the amount and type of wastes in the bins, the result from applying the theoretical calculations indicated that around 2 min were required to reach that concentration. These times were not coincident to the

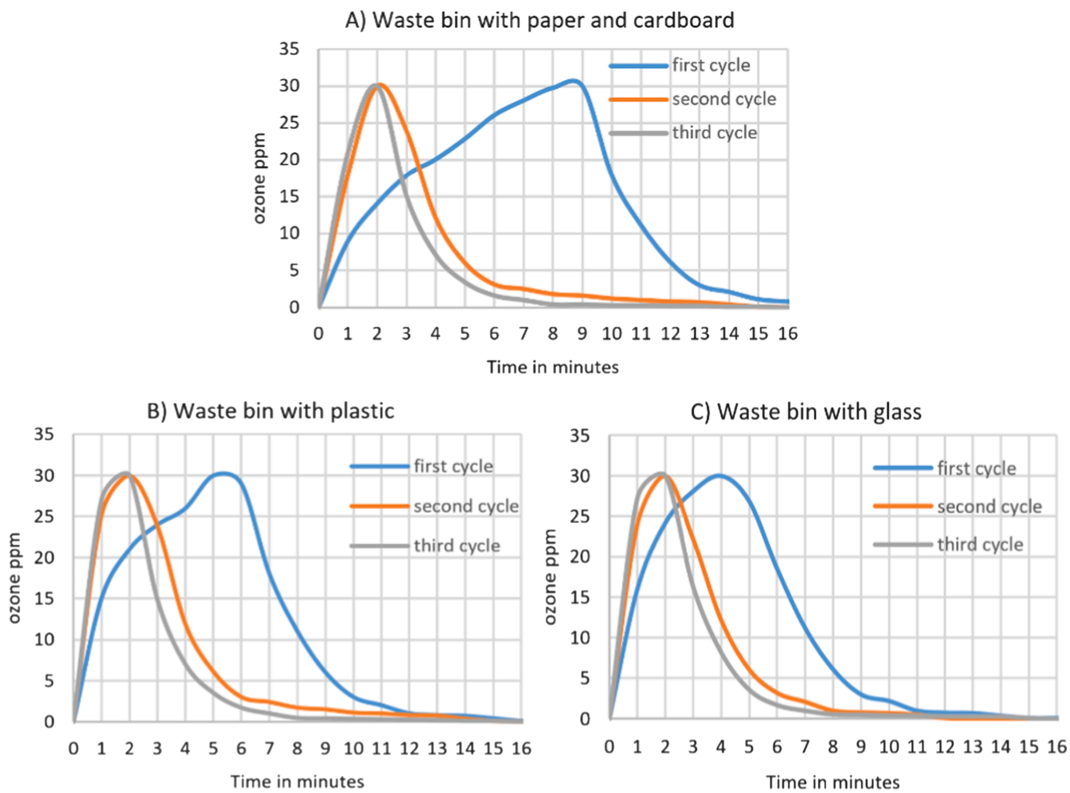
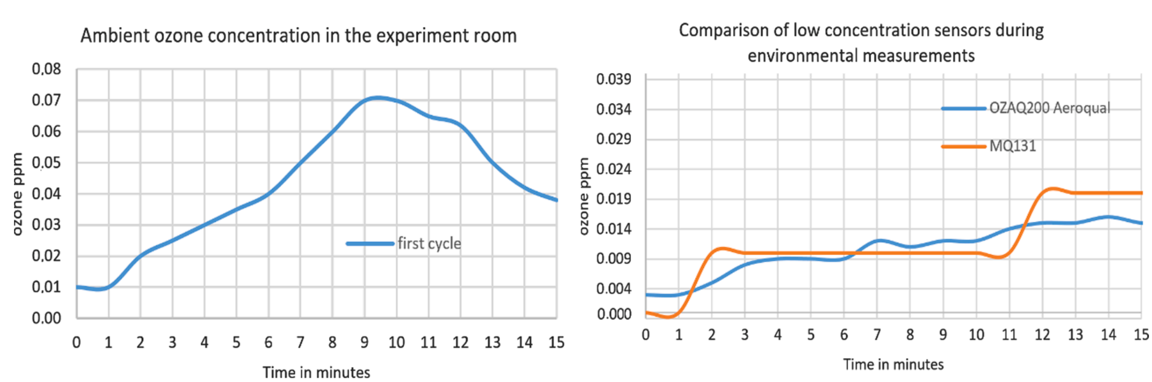


Fig. 5. Ozone levels detected by CJMCU-131 for each waste bin before and after reaching an ozone concentration of 30 ppm in the three decontamination cycles.

experimental results, particularly those related to the first cycles, thus indicating that the theoretical calculations depended on an F factor whose determination was unforeseeable to some extent, at least a priori, because it included several factors in only one. However, these results were close to those obtained from the second cycles, so they were useful to a certain extent to validate both the experimental data (considering that the effect related to the material was not produced in these cycles) and their contribution to the disappearance of the ozone.

After reaching 30 ppm, the ozone disappeared similarly in all the bins, with slight variations. The reason could be the previous and intense exposure to high ozone levels.

There are studies related to the reduction of the ozone when is in contact with several surfaces in indoor environments, thus producing sometimes chemical reactions that contribute to the emergence of other substances (Weschler, 2000). Moreover, some studies have compiled data on the speed of the ozone deposition in several surfaces of different materials (Grøntoft and Raychaudhuri, 2004) and have been useful to understand this issue, also indicating that the speed varies according to relative humidity (greater relative humidity would imply a greater deposition speed); however, it also depends on the type of material, surface, and characteristics. In this case study, a humidity greater than that recorded would have produced not just a greater ozone deposition, but also a disinfection with lower concentration, as previously mentioned by referring to the doses required. The maximum ozone level of 30 ppm was previously established, so the theoretical time required in that hypothetical circumstance would have been lower, thus compensating a circumstance with another. As a result, the humidity in the experiments was valid for the goal of this study. Nevertheless, future research works could study the experiment in detail to corroborate the initial goal in a broader way.



A) B)

Fig. 6. A) Ozone levels detected by MQ131 outside the three waste bins when the ozone generator was applied, reaching the maximum concentration level because the three bins were hermetically closed, and the window and the door of the room were also closed. B) Ozone levels detected by MQ131 and OZAQ300® in the simultaneous environmental measurement performed outside the building.

Considering all these aspects, the results of the experimentation cycles did not maintain the concentration of 10 ppm more than 12 min, so 2 or 3 cycles were required to reach that concentration in the bin with paper and cardboard, and 3 cycles in the other cases.

Fig. 6A) shows the results related to the ozone levels detected by MQ131 outside the three waste bins, with all of them being hermetically closed and the window and the door of the room closed.

The ozone concentration level in the exterior reached a maximum of 0.07 ppm, and the time over 0.05 ppm (the safe threshold established) was barely 6 min.

Regarding the deviations between MQ131 and OZA200 Aeroqual (Fig. 6B) and considering that the former had an accuracy of 0.01 ppm and the latter of 0.001 ppm, in the MQ131 there were no differences more than 0.006 ppm below those recorded by OZA200, or more than 0.007 ppm above those recorded.

On the other hand, if the extractor were activated to extract the residual ozone from the waste bins, the presence of ozone inside the containers would be almost null instantaneously.

4. Discussion

The device presented, which applies the ozone as viricidal, is effective, safe, and useful to re-establish at a low-cost the selective recycling of domestic wastes generated by sick people or in quarantine. However, applying these technologies could be harmful for health and even dangerous in relation to fire and explosion or material deterioration (Linde, 2009), so they should not be applied until the competent authorities approve them.

Regarding the analysis and the discussion of the data of the results, and as Fig. 5 shows, a time between 4 and 9 min was required to reach a concentration of 30 ppm after detecting the first ozone amounts. However, that time depended on both the type of wastes put in the bins and the number of bins that share the ozone injection volume. At first this is not something of a challenge as the times were short and the concentration was appropriate. On the other hand, the ozone level was maintained inside the bins above 10 ppm for approximately 6.5, 7.5 and 10 min for the blue, yellow, and green bins, respectively. These results could be more problematic because, as mentioned by Tseng and Li (2008), a concentration of 10 ppm for approximately 12 min is the way in which the virus is inactivated by 99% under conditions of 55% relative humidity and with a temperature of 25 °C. Thus, several cycles should be applied to guarantee this aspect, thus increasing the risk in case of leaks if cycles are performed subsequently and requiring a greater automation of the device to avoid errors by users.

The maximum amount of ozone detected outside the bins was 0.07 ppm, and this concentration was quickly reduced by disconnecting the ozone generator. Moreover, the indications by Quevedo-León et al. (2020) were fulfilled, although the limit initially established (0.05 ppm) was slightly exceeded (0.07 ppm) for a short time (approximately a few minutes). It was also within the recommendations by OSHA (average over 0.10 ppm for 8 h), NIOSH (upper limit of 0.10 ppm), EPA (0.08 ppm in 8 h), and WHOS (limit of 0.10 mg/m^3 or 0.05 ppm for a daily maximum average of 8 h).

In addition, the immediate effectiveness of the safe extractor to extract the ozone from the bins when necessary or when some leak was detected always guaranteed the lack of dangerous concentrations in the environment of the experiment room. If a leak were detected, the external sensor would automatically activate the extractor and guarantee the safety of people if there would be someone in the room.

If the ozone produced in each experimentation was extracted to the exterior, then a maximum of 3.528 mg would be released. Generally, the disinfection was carried out once per day, so the ozone released was not very significant for environment but for animals, people, sensitive materials or heat sources or fire that are very close to the outlet of the gas. Thus, measures should be established to avoid this aspect. Unlike other disinfectants, the ozone turns into oxygen (with no wastes), so its advantage is evident from an environmental point of view. However, the sum of the amounts released could be studied in detail if this technique would be used worldwide.

Finally, the possible limitations of this study do not prevent from fulfilling the goal established. Thus, the results could be affected by many factors: the type and characteristics of the generator; the volume, number, and characteristics of bins; the type of wastes and their form, amount, dust, and adherent substances; temperature and relative humidity; materials, ventilation, structure, volume, and contents of the experiment room; the gases outside and inside the bins; and the state, accuracy, and calibration at any time of the sensors; among others. Future research studies could therefore experiment by varying and combining these factors. However, the results of this study aimed to provide a methodology and an approach to the verification of the risk of this type of device, so the goal is fulfilled and could be used by future research studies as a basis.

5. Conclusions

The experimentation of this study consisted in putting ozone into bins that kept inside wastes for the recycling chain. The ozone levels were recorded to verify whether these wastes were disinfected, without reaching ozone levels that could be a risk outside the bins.

The results of the experimentation are satisfactory, and the device proposed has been reasonably safe as levels greater than 0.05 ppm were not detected for more than 6 min, or greater than 0.07 ppm in any case. The device is also effective to disinfect in few minutes the wastes to be recycled because enough concentrations were achieved with two or three cycles between 8 and 15 min, when disinfection was considered over. However, the ozone should be studied as viricidal, and the device proposed or other similar devices should be improved for the use indicated and for other uses; experimentations should be carried out by varying and combining the influential factors.

To commercialise or use these technologies, industrial devices designed, manufactured, and commercialised with enough guarantees are required, and they should be rigorously controlled by the competent authorities. Regardless of these aspects, devices should be used in a responsible way by following the indications established by both manufacturers and authorities.

Nonetheless, their use should be isolated because they could have environmental consequences and increase the probability (particularly in the medium or long term) that users do not use them or do not maintain them appropriately (failure to follow the indications, lack of reviews, repairs, replacement in case of breakdowns, verifications, etc.).

To conclude, this study is of interest for engineers and technicians related to waste management. The results have shown a methodology for waste disinfection that could improve sustainable management, which has been affected by the Covid-19 pandemic. Although the device designed in this paper could be used in dwellings with risk of transmission, its use could be extrapolated to several buildings, such as office or commercial buildings. The limitations of the study could be studied by future research works, experimenting with other influential factors, such as other types of wastes and volumes, among others.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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