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Emission rates of indoor ozone emission devices: A literature review

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ABSTRACT

As a strong oxidizing gas, ozone can damage the human respiratory tract and cardiovascular system. Aside from ambient outdoor ozone that enters buildings, indoor ozone emission devices (IOEDs) such as disinfectors, air purifiers, and printing devices are the primary source of indoor ozone. This review briefly presents the types and ozone emission mechanisms of IOEDs, the setups and procedures for measuring the ozone emission rate (OER) of IOEDs, and various equations for analyzing test results. This review also summarizes and compares the OERs of different IOEDs and analyzes the factors affecting the OER. The average OERs of in-duct air cleaners, ozone generators, room air purifiers, photocopiers, laser printers, and other small household devices are 62.8, 76.3, 4.6, 3.3, 0.8, and 0.4 mg/h, respectively. The OERs of in-duct air cleaners and ozone generators are generally larger than those of printing devices. The highest and lowest OERs of room air purifiers in the surveyed literature are 30.5 mg/h and 56 μg/h, respectively, with a difference of approximately 550 times. The ozone emission per unit paper for printing devices and per kilowatt hour for other IOEDs are also calculated and compared. In addition, the effects of the design and working mechanism of IOEDs on the OER are also discussed in detail. Users' operation and daily maintenance of an IOED and the OER test conditions can also affect the OER. Finally, analytical equations are used to compare the influence of the test result processing method on the OER for the same IOED.

1. Introduction

The World Health Organization stipulates that the 8 h average of the ozone concentration should not exceed 0.1 mg/m^3 [1] because ozone is a strong oxidizing gas that can cause negative health effects in humans [2,3]. A large number of studies have shown that the ozone concentration is highly correlated with respiratory-related morbidity, cardiovascular morbidity, and premature mortality [4,5,7,40–44]. Indoor ozone can affect human health and can also react with gaseous chemicals and building materials, resulting in by-products such as C1–C13 carbonyls, dicarbonyls, hydroxyl carbonyls, and secondary organic aerosols [45–48,69–74], which can adversely affect occupants' health and indoor air quality (IAQ) [6,8,9,43,64,96,98]. The indoor ozone concentration depends on the outdoor concentration, the indoor air change rate, indoor ozone sources, and removal by indoor surfaces and gaseous chemicals [96]. Ambient ozone entering buildings and indoor ozone emission sources such as photocopiers, fruit and vegetable washers, and air cleaners [10–33] are usually the two primary sources of indoor ozone. Considering that people spend an average of approximately 90% of their time indoors [34,35], the ozone emission rate (OER) of indoor ozone emission devices (IOEDs) may significantly affect IAQ and occupant health.

In recent decades, household and office appliances such as disinfectors, air purifiers, and printing devices have become quite common [32]. Because of an increased demand for good IAQ, which is an important determinant of human health, comfort, and productivity [36–39], there is growing concern about the levels of ozone emitted by these IOEDs. Diverse ozone emission devices are used indoors, including photocopiers, laser printers, disinfectors, air purifiers, ozone generators, and other household appliances. The most common disinfectors are fruit and vegetable washers, laundry/drinking water treatment devices, shoe sanitizers, and facial steamers. Air purifiers are a very important and abundant source of indoor ozone and include room air purifiers, in-duct air cleaners, refrigerator air purifiers, car (dashboard) purifiers, and wearable air purifiers. Wearable air purifiers, which are small portable devices, can be worn around the human neck and purify the air near the mouth and nose. Other household appliances such as pet brushes and ionic hair devices have also been tested for their ability to generate ozone [10,32]. Owing to their operational requirements, the above devices produce a corona discharge or emit ultraviolet (UV) light, providing possible conditions for ozone generation in the absence of protective measures. In addition to the IOEDs mentioned above, another type of device, which are called ozone generators in this paper, intentionally generates ozone to decontaminate occupied spaces

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Nomenclature

A	The area of indoor surface (m^2)
A_h	The area of human surface (m^2)
A_p	The area of tested device surface (m^2)
A_{duct}	The cross-sectional area of the duct (m^2)
C_{in}	The indoor ozone concentration (mg/m^3)
$C_{in-duct}$	The ozone concentration inside the duct (mg/m^3)
$C_{downstream}$	The downstream ozone concentration of the duct (mg/m^3)
$C_{upstream}$	The upstream ozone concentration of the duct (mg/m^3)
$C_{in(0)}$	The initial indoor ozone concentration (mg/m^3)
$C_{in(T)}$	The indoor ozone concentration during the period of one cycle of use (mg/m^3)
C_e	The equilibrium concentration of indoor ozone (mg/m^3)
C_{off}	The indoor ozone concentration when the device is turned off (mg/m^3)
C_{supply}	The ozone concentration in the supply air (mg/m^3)
C_{out}	The outdoor ozone concentration (mg/m^3)
C_j	The indoor concentration of gaseous chemicals j (mg/m^3)
E	The ozone emission rate of the device (mg/h)
E_{eff}	The effective ozone emission rate of the device (mg/h)
E_p	The ozone emission rate of the printing device (mg/(h·copier))
F	The short-circuiting factor (−)
i	The number of total data points (−)
Σk	The total ozone removal rate by indoor surfaces, tested device surfaces, human surfaces, the sum of gaseous chemicals through chemical reactions and self-dissociation (h^{-1})
k_d	The constant for ozone's removal by indoor surfaces (h^{-1})
k_h	The constant for ozone's removal by human surfaces (h^{-1})
k_p	The constant for ozone's removal by tested device surfaces (h^{-1})
k_a	The constant for ozone's removal by absorption of indoor air (h^{-1})
k_{di}	The constant for ozone's removal by self-dissociation (h^{-1})
k_j	The rate constant for the reactions between ozone and gaseous chemical j ($m^3/(mg{\cdot}h)$)
k_r	The deposition rate constant of ozone resulted from the surface reaction (h^{-1})
k_D	The rate constant of ozone desorption from the chamber wall (h^{-1})
M	The mass of ozone adsorbed on the sink surface (mg/m^2)
M_i	The initial slope of the ozone growth curve ($mg/(m^3{\cdot}h)$); n and n + 1 The consecutive data points (−)
P	The ozone penetration factor (−)
Q	The average volumetric flow (m^3/h)
T	The duration of device within one cycle of use (h)
t	The monitoring time (h)
V	is the indoor volume (m^3)
ν	The average flow velocity of the duct (m/h)
ν_d	The ozone deposition velocity of the indoor surface (m/h)
ν_h	The ozone deposition velocity of the human surface (m/h)
ν_p	is the ozone deposition velocity of the tested device surfaces (m/h)
γ_{filt}	The ozone removal efficiency of the filters of the air cleaner (−)
λ	The air change rate (h^{-1})
λ_0	The air flow rate through the air cleaner (m^3/h)
Δt	is the time interval between two data points (h)

or surfaces. In theory, any IOED that can produce ozone can be called an ozone generator. However, in this article, "ozone generator" refers specifically to IOEDs that are not included among the devices mentioned above but still intentionally emit ozone. For example, these IOEDs, such as commercial NO_x generators [18], dedicated ozone generators [33], sanitizing wands [32], and air purifiers designed to produce ozone intentionally [10], are all defined as ozone generators in this paper. Even though fruit and vegetable washers and shoe sanitizers also intentionally emit ozone to decontaminate object surfaces and are considered to be a particular type of ozone generator, we list them separately in this review. The IOEDs in the literature are summarized in Table 1.

Previous studies have shown that IOEDs emit different amounts of ozone depending on the type, brand, and model of the device. For instance, numerous investigations have monitored the OERs of different brands and models of room air purifiers in various environments [13,14,18,20–22,26,29,31,33]. Britigan et al. [10] measured the OERs of 13 types of air purifiers and disinfectors in various indoor environments at 40%–50% relative humidity (RH), including offices, bathrooms, bedrooms, and cars. Dry-process photocopiers and laser printers emit significant amounts of ozone during operation, which has been confirmed by other researchers [11,15–17,27]. Zhang et al. [32] tested the OERs and impacts on indoor ozone levels and associated exposure of 17 consumer products and home appliances that could emit ozone either intentionally or as a by-product of their functions. Morrison et al. [19], Poppendieck et al. [24], Xiang et al. [30], and Gunter [79] found that in-duct air cleaners emitted very large amounts of ozone, which can harm human health. Wearable air purifiers also release a small amount of ozone directly into the user's breathing area, which greatly increases the level of ozone exposure of the human body [23,25].

In view of these significantly adverse health impacts of human exposure to indoor ozone, global standards or guidelines for ozone concentration limits have been established for ozone emission devices. For instance, the US Food and Drug Administration requires that the ozone output of indoor medical devices be no more than 50 ppb, whereas Underwriters Laboratory Standard 867 [105] limits the ozone output of household electrostatic air cleaners to no more than 50 ppb under standardized ventilation conditions. Detailed review articles have focused on indoor ozone. Fadeyi [95] reviewed the research on the chemical reactions and concentration of ozone in the indoor

Table 1

Classification of IOEDs in published literature.

Device Type	Ozone Emission Mechanism	Not Intentional /Intentional[a]
Photocopier	Corona discharge	Not Intentional
Laser printer		
Wearable air purifier		
Pet brush		
Ionic hair device		
Fruit and vegetable washer	Corona discharge	Intentional
Refrigerator air purifier		
Laundry/Drinking water treatment device		
Shoe sanitizer	Photochemistry	Intentional
Facial steamer		
Room air purifier	Corona discharge/ Photochemistry	Not Intentional
In-duct air cleaner		
Car (dashboard) purifier		
Ozone generator[b]	Corona discharge/ Photochemistry	Intentional

[a] Not intentional emission means ozone is generated as by-product during the device working period; Intentional emission indicates that the device is used to generate ozone intentionally.

[b] The ozone generator here refers to the IOED that intentionally produce ozone in addition to the device already listed.

environment over the past 15 years and summarized the impact of ozone on human health. Wells et al. [6] summarized the sources of indoor oxidizing substances, focusing on the impact on human health and comfort. Shen et al. [68] and Darling et al. [78] presented detailed reviews of ozone surface removal on building material surfaces and passive removal materials, respectively. Destaillats et al. [99] summarized the indoor pollutant groups emitted by office devices, including ozone, particulate matter (PM), volatile organic compounds (VOCs), and semivolatile organic compounds. However, these studies did not focus specifically on the OERs of IOEDs. Hence, this paper attempts to provide a detailed review of the OERs of IOEDs based on previous published investigations. Moreover, the relationship between the OER and energy consumption is also presented.

The scientific literature reviewed in this paper was identified by searching ISI Web of Science and ScienceDirect. In addition, Google Scholar was used as a supplementary search. As a source of search records, the following keywords were used: ozone emission rate; ozone generation source; indoor ozone; laser printers; photocopiers; air purifiers; disinfectors; ozone generators; ozone devices; corona discharge; photochemical mechanism; surface removal; deposition velocity; morbidity; occupant health.

Articles and publications were considered for inclusion according to the following criteria:

- Original research articles in English
- Articles relevant to the key research questions identified
- Publications up to December 2018.

2. Ozone emission mechanism

The ozone emission mechanisms of IOEDs can generally be classified into two categories: photochemical mechanisms and corona discharge mechanisms. Photochemical mechanisms are used in devices with internal UV light, e.g., sanitizing wands, facial steamers, and shoe sanitizers [32]. Corona discharge is typically used in photocopiers, laser printers, and other home appliances such as ionic hair devices and pet brushes [10]. Most wearable air purifiers and refrigerator air purifiers adopt negative ion generation by corona discharge. Some other air purifiers such as room air purifiers, in-duct air cleaners, and car (dashboard) purifiers may use either a photochemical mechanism or a corona discharge mechanism. These are called UV lamp air purifiers and ion air purifiers, respectively. Ozone generators are designed to produce ozone intentionally; they can use either a UV lamp or corona discharge for ozone emission. Various IOEDs are summarized in Table 1 according to their ozone emission mechanisms and whether they intentionally emit ozone.

2.1. Photochemical mechanism

Photochemical generation of ozone occurs by oxygen decomposition and recombination to form ozone under UV irradiation. Ozone is emitted during the working period of the UV lamp in air purifiers and disinfectors. Mercury-based UV lamps, in particular low-pressure mercury lamps, are the most commonly used in disinfectors and purifiers. Mercury lamps are described as low-pressure and medium-pressure lamps according to the mercury vapor pressure during lamp operation (approximately 1 Pa and greater than 100 kPa, respectively) [88]. The spectral radiation from a low-pressure lamp is dominated by the two ground-state resonance lines at 254 and 185 nm, and the UV spectrum of a medium-pressure lamp is polychromatic [63]. Because UV radiation with wavelengths between 200 and 300 nm can be absorbed by DNA, disrupting its structure and leading to deactivation of living cells, mercury lamps, especially low-pressure mercury lamps, operating in this band are often used to inactivate microorganisms and reduce pathogen transmission. During sterilization using the 254 nm radiation of a low-pressure lamp, the 185 nm emission of the lamp can generate ozone through oxygen photolysis and further reactions [49–51,55]:

$$O_2 + h\nu(185\,\mathrm{nm}) \rightarrow O(^1D) + O(^3P) \tag{R1}$$

$$O(^1D) + B \rightarrow O(^3P) + B \tag{R2}$$

$$O(^3P) + O_2 + B \rightarrow O_3 + B \tag{R3}$$

where B could be either the O_2 molecule or N_2 molecule. $O(^1D)$ refers to an oxygen atom in the excited metastable state, and $O(^3P)$ refers to an oxygen atom in the ground state. Further, $h\nu$ is the photon energy, where h is the Planck constant, and ν is the frequency.

During the working period of a low-pressure lamp, one oxygen molecule is broken into two oxygen radicals [50]. Activated oxygen radicals then recombine with oxygen molecules to produce a free-radical chain reaction and hence form ozone. Note that ozone can also be decomposed and returned to oxygen under emission between 200 and 308 nm [55]. Therefore, the 254 nm spectral line of the low-pressure lamp can be used to both limit microorganism growth and inhibit ozone generation. Generation and elimination of ozone by low-pressure lamps are simultaneous. Ozone decomposition by the 254 nm emission of the lamp occurs through the following reactions [49,50,52,53].

$$O_3 + h\nu(254\,\mathrm{nm}) \rightarrow O_2 + O(^1D) \tag{R4}$$

$$O(^1D) + O_3 \rightarrow O_2 + 2O(^3P) \tag{R5}$$

$$O(^3P) + O_3 \rightarrow 2O_2 \tag{R6}$$

2.2. Corona discharge mechanism

Corona discharge is widely used in printing devices, air purifiers, and some household appliances. Ozone is produced as a by-product during discharge. The ozone generation mechanism can be simply described by the following two steps [56–59,102]:

$$O_2 + e \rightarrow 2\ O + e \tag{R7}$$

$$O + O_2 + B \rightarrow O_3 + B \tag{R8}$$

where e stands for the electron, and B could be either the O_2 molecule or the N_2 molecule. Ozone can be generated in a strong electrostatic field through a reaction sequence involving electrons, free radicals, and oxygen during charging. Wang et al. [75] studied the differences in ozone production by the photocatalytic and corona discharge mechanisms. They showed that the highest ozone yield that can be achieved by electric discharge in oxygen is 150 g/kw·h, and the highest ozone yield achieved by photocatalysis between 185 and 254 nm is 25 g/kw·h.

2.2.1. Printing devices

Printing devices includes photocopiers, laser printers, and all-in-one office machines containing a color printer, fax, copier, and scanner. The basic steps used in printing devices are shown in Fig. 1. First, a uniform charge is imparted to the photoconductive drum. Then the original image is reflected by a mirror onto the drum surface during the exposure step. The image is developed when negatively charged toner particles or aerosols are attracted to the positively charged areas of the image on the drum. As the paper passes through, the negative particles on the photoconductive drum stick to the paper. Next, the image is fixed on the paper by heating. Finally, the photoconductive drum is cleaned by a print scraper in preparation for the next copy image. During printing, a certain amount of ozone may be generated in the first charging step by dissociation of oxygen by the heat generated and the electric energy [15], as shown in Fig. 1.

2.2.2. Air purifiers and disinfectors

Air purifiers and disinfectors can be either portable or stationary. Portable air purifiers include room air purifiers, car (dashboard) purifiers, and wearable air purifiers [10,25,32]. Stationary purifiers are

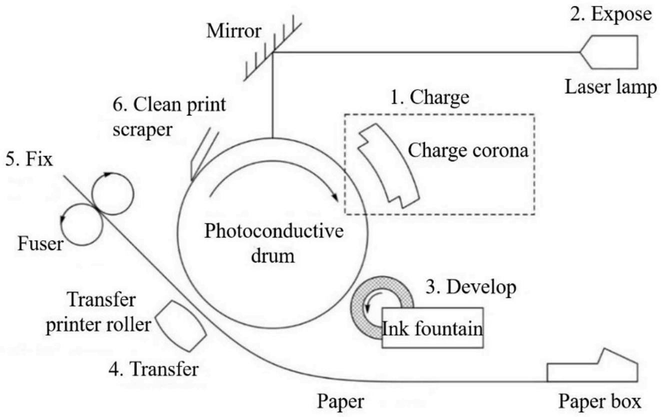

Fig. 1. Basic steps in laser printing. Adapted from Ref. [62].

usually in-duct air cleaning devices, which are permanently mounted in the ductwork of heating, ventilation, and air conditioning (HVAC) systems. Disinfectors include pet brushes, fruit and vegetable washers, and laundry water treatment devices [10,32]. Two different forms of corona discharge used in air purifiers and disinfectors are shown in Fig. 2. Under an electrostatic field surrounding an electrode wire or pole held at a high voltage relative to ground potential, gas molecules and particles are charged and attracted to an oppositely charged plate or other medium. Later, contaminants are collected at the dust collection plate by charge neutralization. This dedusting device is usually called an electrostatic precipitator (ESP). The ESP is widely applied in air purifiers, especially stationary air cleaners. Ozone is formed in the discharge process of a high-voltage electrode line or point. Portable air purifiers can use the ESP as well, but they more often use an ionizer instead. Ionizers have a mechanism analogous to that of the ESP but have no oppositely charged collection media. Instead, gas molecules and particles are removed owing to an increase in their self-deposition rate [19]. Unipolar ions (usually negative) emitted from the ionizer help to charge the airborne particles, which are then removed from the air space by electromigration to the walls of the room owing to variation of the electromagnetic field intensity in space [100,104]. Another commonly used portable air purifier is the non-thermal plasma air purifier. Non-thermal plasma air purifiers use corona discharge with alternating current to generate plasma for air purification. Under an external electric field, high-energy electrons form in Non-thermal plasma air purifiers and can bombard particles and gas molecules. These particles are ionized to form a plasma and then produce dissociation by colliding with each other, resulting in air purification [101]. Ozone is generated during plasma formation by alternating current corona discharge [13,64].

Adding filters, such as high-efficiency particulate air filters, activated carbon filters, mini-bag filters, and electronically enhanced filters, to air cleaners is also a common method of purifying air. Filters usually do not produce any ozone, but they may significantly affect the actual (net) OER of the device owing to potential ozone elimination on them. Some studies have considered the impact of filters on the OER, as discussed in more detail in section 5. Most air purifiers use a hybrid system that may include a combination of a UV lamp, filters, an ESP, or an ionizer to enhance the purifying effect.

3. Ozone emission rate measurement

3.1. Test environment

Two types of test protocols for ozone emission, direct and indirect tests, are summarized after a review of the literature [12,14]. In indirect testing, the OER of IOEDs is assessed by monitoring the indoor ozone concentration emitted by the IOEDs into the ambient environment. Indirect tests can be divided into face tests and room tests according to the measurement accuracy. Face tests can roughly determine the OER by measuring the ozone concentrations around the exterior face of the IOED [17], as shown in Fig. 3A. Room tests are used to monitor the average concentration of indoor ozone under uniform mixing. Room testing usually requires a mixing tool to mix the indoor air. Direct testing is used to obtain the OER of IOEDs by monitoring the ozone concentration and gas flow in ductwork that is attached directly to the exhaust port of the IOED [12,14,19,79], as shown in Fig. 3B. Direct testing is a more efficient way to assess the OER of IOEDs than indirect testing in the majority of cases. However, direct testing works only for IOEDs such as air purifiers that have a self-ventilation function, so indirect testing is generally used for most household and office appliances. Previous studies of indirect tests usually involved an environmental chamber test, as shown in Fig. 4, or a field test, as shown in Fig. 3, to determine the OER of IOEDs. Face testing is usually performed in the field, and room testing is conducted in an environmental chamber. Depending on the research requirements, the volumes of chambers in the literature [11,13,15,16,18–23,25,29,31,33,79] are between 0.46 and 33.6 m^3. Some organizations and standards have also suggested the chamber size for indirect testing. GB/T 18801-2008 [103] stipulates that the volume of testing chambers for household air cleaners must be 30 m^3. Underwriters Laboratory Standard 867 [105] suggests that the volume of the chamber be between 26.9 and 31.1 m^3 to evaluate ozone emission. Field study locations include common indoor spaces, such as washrooms, meeting rooms, offices, and bedrooms [12,14,22,23,26]. In addition, there are also distinctive test environments such as cars, air ducts, and refrigerators [10,19,24,30,32]. The experimental conditions of ozone investigations are described in Table 2.

Three main types of chambers are used depending on the IOED size and the airflow pattern in the actual situation. One is suitable for medium-sized devices such as printing devices and portable air purifiers, as shown in Fig. 4A. According to the comprehensive consideration of the chamber volume and equipment size in Table 2, we refer to chambers more than 1 m^3 in size as medium-sized environmental chambers. Tests in medium-sized environmental chambers can adopt single-pass airflow, which provides supply air and exhaust air, or circulation airflow, which adds a return air system on the basis of single-pass airflow. During the room test, the sample ozone concentration can be monitored continuously in the exhaust air [11] or return air [22] from the well-mixed chamber using an ozone analyzer. The well-mixed condition can be verified through a mixing condition test, as described by Shi et al. [25]. To ensure the accuracy of the OER obtained by testing, ozone deposition in ducts and leakage at junctions should be considered when the circulating airflow test is used in the chamber. In addition, the indoor ozone concentration at a specified location in the room can be tested as the average ozone concentration. Note that this sampling method for room testing is very similar to the face testing sampling method, in which points around the device are monitored. The difference is that this sampling method for room testing generally uses a mixing fan and includes verification that the room is well-mixed. The face testing sampling method does not use a mixing tool such as a mixing fan and does not indicate whether the indoor ozone

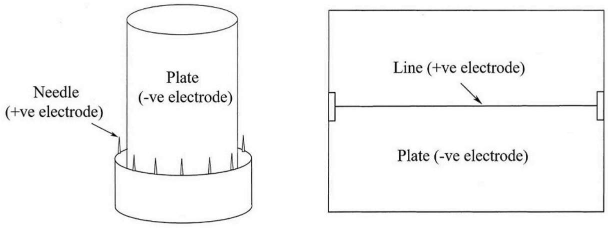

Fig. 2. Schematic diagram of two types of corona discharge used in air purifiers and disinfectors. Adapted from Refs. [20–22].

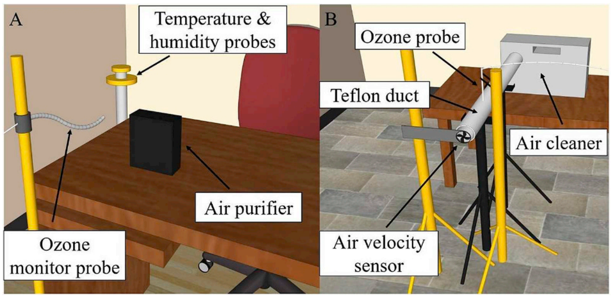

Fig. 3. Three-dimensional models of field test setups adapted from Ref. [12]: (A) face test in office, and (B) direct test in warehouse.

concentration is consistent. Another difference is that room testing is generally performed in a chamber, whereas face testing is performed in the field. Because the ozone emitted by a device is not evenly distributed in the environment, the ozone concentration monitored by face testing is not necessarily the average indoor ozone concentration. However, in some studies, the ozone concentration monitored by face testing was treated as the average concentration. Thus, in this paper, we consider that face testing is an imprecise means of testing.

The second type of chamber is suitable for small devices such as pet brushes and wearable air purifiers, as shown in Fig. 4B. We refer to chambers less than 1 m^3 in size as small environmental chambers based on comprehensive consideration of the chamber volume and device size. In most studies, mini-chamber and Tedlar bag systems were chosen as the test environment for small devices [10,23,25]. Sampling can be performed in mini-chambers by the same processes as in medium-sized chambers. For the Tedlar bag system, as shown in Fig. 4B, a common method is to cover a small device with a transparent glass cylinder and collect ozone samples using a Tedlar bag and Teflon line.

The third type is applicable only to in-duct air cleaners, as shown in Fig. 5. Fig. 5A illustrates the experimental apparatus for measuring the OER of an in-duct air cleaner. This closed-loop chamber system is specially designed for in-duct air cleaners and includes upstream and downstream sampling equipment, a test section, air handling equipment, a flow station, high-efficiency particulate air filters, and activated carbon filters. The test section is the duct segment in which the air cleaners are installed. The pressure distribution is calculated by the air handling units, and the flow station can measure the airflow rate accurately. High-efficiency particulate air filters and activated carbon filters are located upstream of the test section to eliminate particulates and ozone in the airflow. The upstream and downstream sampling equipment is designed to achieve a representative ozone sample called a sampling grid, illustrated in Fig. 5B. The ozone analyzer is connected to the top of the sampling grid system to analyze the ozone emission. The main interior surface materials of the three types of chambers are inert materials such as stainless steel, galvanized steel, aluminum, and glass to minimize any potential sink effects. Purified air with a target temperature, humidity, and ozone background concentration is introduced into the chamber at the desired airflow rate.

The field test helps clarify the ozone emission characteristics of a device in real-world operation. To simulate real-world ozone emission, the actual surface material and original dimensions of the room in the field are retained as far as possible without modification. Before testing, the initial indoor/outdoor ozone concentration, air exchange rate, and ozone removal rate need to be measured in the field. Most field tests use face testing [12,32], as shown in Fig. 3A, or direct testing, as shown in Fig. 3B. Fig. 3A shows a field scene of face testing in an office, in which ozone monitor probes were placed near the device. Fig. 3B shows direct testing of a room air purifier in a warehouse; the ozone probe was inserted into a Teflon duct connected to the exhaust port of the air cleaner. There are many uncertainties in measuring the OER of IOEDs in the field, and direct testing is a better method than indirect testing. When face testing is the only option, it may be possible to improve the monitoring accuracy by distributing multiple monitoring points around the IOED and averaging multiple measurements.

3.2. Test procedure

ISO/IEC 28360 [76] describes the standard procedure for testing the OER of electrical equipment. In addition, Leovic et al. [16] also described the test procedure for measuring the OER of dry-process photocopy machines in detail. On the basis of the published literature, we summarize and briefly describe the important test steps for determining the OER of IOEDs. First, it is necessary to assess the potential leakage and deposition effects of the chamber [17,18]. In addition, it is also very important to measure the ozone removal rate in the field. Ozone removal can be verified before formal testing or after completion of the entire test. Before testing, the indoor and outdoor concentrations in the field test and the initial ozone concentration in the chamber need to be determined. The air change rate of the chamber and field should also be known in advance. IOEDs are often placed on the floor or a desk and should be situated in the center of the test environment [12,14,22,25,32]. During face testing, the air sampling probe for ozone is placed selectively near the IOED, where the sample location is above the floor within 0.5–1.5 m [27,32] and 0.1–0.9 m of the device outlet or surface [23,25,32]. In room tests, the sample ozone concentration in a well-mixed chamber is determined by analyzing the average ozone concentration in the exhaust air, return air, or indoor air [11,22,25]. Small devices can be covered by a glass cylinder and sampled through a Teflon line. For in-duct air cleaners, the sampling grid shown in Fig. 5B has been used [19]; it consists of 15 sampling points 1 mm in diameter evenly distributed on three vertical stainless steel rods. The cross section of the duct is covered by sampling at 15 preset locations within the duct, where the probes are kept perpendicular to the airflow, and all the

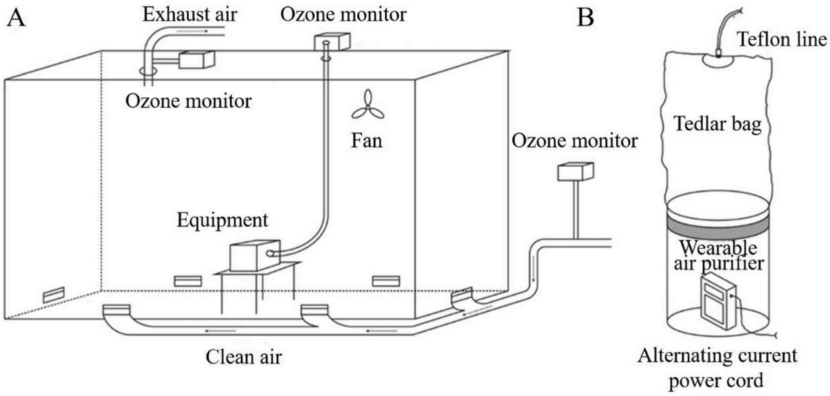

Fig. 4. Schematic of environmental chamber (A) and Tedlar bag system (B). Adapted from Refs. [18,23].

Table 2
Experimental conditions of OER in published literature.

Device	Product	Technology	Environment	V[m^3]	Material	T[°C]	RH[%]	ACH[h^{-1}]	C$_{out}$[ppm]	Deposition rate [h^{-1}]	Reference
Portable air purifier	NA^{c}	Ion^{b}	Room	300	NA	NA	50–80	0.4	0	NA	[28]
	Eagle 5000 ozone generator & Living Air XL-15	Ion (N)^{b}/FS^{b}	Bathroom	4.2	Typical^{c}	NA	NA	NA	0	NA	[26]
			Storage shed	17.9	Concrete						
	Teco Model 100	NA	Chamber	30	SS^{c}	NA	30/50/70	1/5	NA	Around 1.29	[18]
			House	Around 334.5	Typical^{c}	21.1	15–29	0.35–0.48		NA	
	NA	HS^{b}	Chamber	6.4	SS	20–24	Around 60	NA	0.002–0.004	0.22–2.88	[20,21]
	NA	Ion	Chamber	6.4	SS	NA	NA	NA	0.002–0.003	0.0948–0.259	[22]
	NA	Ion	Chamber	11	SS	NA	NA	2.73–6.8	ND^{d}	NA	[33]
	A^{a}	Ion	Office	20	Typical^{c}	NA	NA	0.27	0.0008–0.0118	NA	[12]
			Teflon duct	14.25	Teflon			0.38–3.13			
	B^{a}	Ion/ESP	Bathroom	5.9/10.4/31.4	Typical	NA	40–60	NM^{d}	NA	1.13–5.45^{e}	[10]
			Office	27.1/35.2	Typical		35–45	Around 0.2		Around 5	
			Teflon bag	0.7	Teflon		< 5	0.13		NA	
	NA	ESP/Ion	Chamber	14.75	SS	NA	NA	0.5	0	4	[29]
	C^{a}	ESP/Ion/UV	Office	20	Typical	NA	32.9–47.6	0.27	0.0003–0.0179	NA	[14]
	NA	Ion/FS(C)^{b}	Chamber	11.132	SS	24–26	55–65	1	0.002–0.005	Around 0.013	[31]
	NA	PCO/UV/Ion (P)^{b}/FS(C)/Ion	Chamber	20	SS	24–33	22–49	0.33–0.66	0.0014–0.003	0.56–0.72	[13]
Wearable air cleaners	NA	Ion	Mini-chamber	NA	Glass	24–28	33–37	NA	0.003–0.005	NA	[23]
	NA		Office	30	Typical			Around 1.41			
	Ioncare portable air purifiers	Ion	Cylinder& Teflon bag	0.4–0.7	Plexiglas &Teflon	NA	< 5	0.13–0.225	0	NA	[10]
	NA	Ion (N)	Mini-chamber	0.46	SS	NA	NA	0.0307	0	NA	[25]
Car Air Purifier	E^{a}	UV/Ion	Car	1.4	Typical^{c}	15	40–60	NM	NA	20^{e}	[10]
			Teflon bag	0.4	Teflon	NA	< 5	0.225	0	NA	
Refrigerator air purifier	NA	Ion	Room	13.8	NA	NA	NA	0.7–1.4	< 0.005	NA	[32]
In-duct air purifier	NA	UV/ESP	Closed-loop chamber	Around 6.62	SS&GS^{c}	Around 10& Around 50	20–30& 50–70	75.5–302	NA	NA	[79]
	D^{a}	UV/ESP/PCO	Closed-loop chamber	Around 9.08	SS&GS	22.3–44.4	15.4–71	55–275	NA	NA	[19]
		FS(C)	House	199–431	Typical^{c}	9.3–34.1	15.3–72.6	0.14–0.93	0.0009–0.0049	2.02–7.5	
	NA	ESP	Bedroom	340	Typical^{c}	Around 21	Around 34.6	Around 0.31	Around 0.002	Around 1.1	[24]
	NA	ESP/FS(E)^{b}	Office	960	Concrete flooring Gypsum ceiling tiles	Around 22.7	Around 45.6	Around 1	0.002–0.007	2.6–3	[30]
Printing device	NA	Corona discharge	Chamber	22.6981	SS/Al/Viton	26–31	30–35	1.8–2.2	ND	NA	[16]
	NA	Corona discharge	Laboratory	22.7–35.4	Al/Marlite/SS walls SS/GS/Vinyl floor Marlite ceiling	26–31	30–35	0.904–1.88	ND	NA	[17]
	NA	Corona discharge	Chamber	33.6	SS	22.5–23.5	45–55	1.95–2.05	< 0.00051	NA	[11]
	F^{a}	Corona discharge	Room	20.4/40	NA	NA	NA	0.03/1.5	ND	2/NA	[27]
	NA	Corona discharge	Chamber	2.376	SS	21–25	50–60	NA	NA	NA	[15]

(*continued on next page*)

Table 2 (*continued*)

Device	Product	Technology	Environment	V[m^3]	Material	T[°C]	RH[%]	ACH[h^{-1}]	C_{out}[ppm]	Deposition rate [h^{-1}]	Reference
Pet brush	Sharper Image IB Pet Brush	NA	Teflon bag	0.4–0.7	Teflon	NA	< 5	0.13–0.225	0	NA	[10]
Fruit and vegetable washer/ Facial steamer/Shoe sanitizer	NA	UV	Room	13.8	A wooden table & chair Vinyl tile floor & Aluminum with an inactive coating in interior surface	NA	NA	0.7–1.4	< 0.005	NA	[32]
Laundry water treatment device	NA	NA	Bathroom	10.9	Typical	NA	NA	Around 0.4	< 0.005	NA	[32]

[a] A = AIpine XL-15 &Lightning Air RA 2500(Ionizer); Biozone® 500(Ionizer(N)); Prozone®Whole House(NA); Prozone®Compact (NA); B = Sharper Image Quadra Silent Air-Purifier (Ionizer); EZ-COM Air Purifier (NA); Air-Zone XT-400 (NA); Prozone Air Purifier (NA); OzoneTM PRO420 Ozone Generator (Ozonolysis); Sharper Image Electrostatic Air Cleaner (ESP); Sharper Image Air Freshener 2.0 (NA); C = Oreck Super Air 8 Sharper (ESP/Ionizer); Image™ Ionic Breeze® GPb (ESP/Ionizer/UV); Sharper Image™ Ionic Breez ®Quadra® Pro (ESP/Ionizer); Sharper Image ™ Ionic Breez® Quadra®Compact (ESP); Sharper Image ™ Ionic Breeze®Air Freshener (Ionizer); D = Dust Free Bio Fighter Lightstick (UV); Guardian Air by RGF(ESP); Honeywell F300 Electronic Air Cleaner(UV); Lennox PureAir Air Purification System (UV); ActivTek INDUCT 2000(UV); Air-Zone Air Duct 2000 (Ozone generator); APCO Fresh-aire (PCO/UV Filters systems(C)); HVAC UV 560 (UV); E = Sharper Image GP Car Air Purifier with UV Germicidal Protection (UV light); Sharper Image Dashboard (Plug-In) Ionizer (Ionizer); Sharper Image Car Air Purifier (NA); F = HP Laser Jet II of Printer; HP Laser Jet 5L of Printer; HP Laser Jet III of Printer; Agfa photocopier of model X88/STS/8.

[b] ESP = Electrostatic precipitator; Ion (N) = Negative ion generator, Ion (P) = Plasma ion generator, Ion = Ion generator (no special description of the working mechanism); UV = Ultraviolet light bulbs, PCO = Ultraviolet light bulbs and Photocatalytic Oxidation system; Filters systems (FS): FS (C) = Activated carbon filters; FS (E) = efficient filtration system; Hybrid systems (HS) = Combine multiple technologies.

[c] SS = Stainless steel; GS = Galvanized steel; Al = Aluminum; Bedroom = The room had ordinary flooring and painted wallboard construction for the walls and ceiling. Standard bedroom furniture; Office = The room had ordinary flooring, painted wallboard construction for the walls and ceiling, standard office furniture; Bathroom = No furniture and fairly unreactive surfaces (ceramic tile, glass, enamel painted walls, etc.); Car = Stationary unoccupied car with leather seats and carpeted floors; House = A ordinary household which has been decorated and resided.

[d] NA = Not available in the literature; NM = No measurement in the literature; ND = No detection in the measurement in the literature.

[e] The total decay rate including the air change rate.

data points are averaged. After the preliminary preparation, the monitoring apparatus and IOED can be operated until the mean ozone concentration of the chamber reaches equilibrium. The OER can be obtained by collecting data samples and applying the equation presented in section 3.3.

In some cases, the mean ozone concentration cannot reach a steady state or takes a long time to become stable. Ozone emission can be monitored in one working cycle of devices, especially for household appliances such as laundry water treatment devices and shoe sanitizers, and the average OER can be calculated later by data processing [32]. Regarding office appliances, the operating modes of printing devices include power off, idle, printing, and sometimes power-saving modes. Note that ozone can be detected only in printing mode when a certain quantity of paper is in the cassette. If the indoor ozone concentration cannot stabilize owing to limited paper capacity, the printing device can be remotely controlled to continue printing without opening the environmental chamber. Brown [11] printed at intervals to ensure that the photocopier had sufficient time to release enough ozone to reach equilibrium in the chamber. There are also additional factors to consider when testing car (dashboard) purifiers. For instance, testing has been performed in an unoccupied car at dusk at 15 °C to avoid possible by-products from heating of the vehicle by the sun to minimize the effect of variations in the ambient ozone level [10].

3.3. Data analysis process

As illustrated in Table 3, data analysis is divided into four types: direct algebraic computation, the single-zone steady-state model, the single-zone transient model, and the two-zone model. Algebraic computation is used in direct testing, whereas the other three methods are used in indirect testing.

3.3.1. Direct algebraic computation

As shown in Fig. 3B, because the ductwork is connected directly to the exhaust port of the IOED in direct testing [12,14], the parameters $C_{in-duct}$, ν, and A_{duct} can be obtained directly using appropriate instruments to determine the OER. Then the OER can be calculated as

$$E = Q\cdot C_{in-duct} = \nu\cdot A_{duct}\cdot C_{in-duct} \tag{1}$$

Because in-duct air purifiers have their own pipelines, it is possible to not only directly monitor the parameters in the pipeline to calculate the OER, but also to use indirect testing. For indirect testing, refer to the single-zone model described in sections 3.3.2 and 3.3.3, especially Eqs. (11) and (12). For direct testing, as shown in Fig. 5A, some studies [19,79] used Eq. (2) to directly calculate the OER of in-duct air purifiers in chamber tests. Because the upstream ozone can be completely adsorbed by the filters, it can also usually be simplified to Eq. (1). If direct testing is performed in a real environment [30], it is necessary to consider the impact of outdoor ozone entering the duct and partial removal of ozone by filters in the pipeline. It is possible to establish the mass balance equation [Eq. (3)] for ozone in the supply air to obtain the OER. Then, Eq. (3) can be rearranged to obtain Eq. (4).

$$E = Q\cdot(C_{downstream} - C_{upstream}) \tag{2}$$

$$C_{in-duct} = (1-\gamma_{filt})\cdot C_{out} + (1-\gamma_{filt})\cdot\frac{E}{Q} \tag{3}$$

$$E = \frac{[C_{in-duct} - (1 - \gamma_{filt})\cdot C_{out}]\cdot Q}{(1 - \gamma_{filt})} \tag{4}$$

Eqs. (1), (2) and (4) have the same form, in which the OER is equal to the product of the flow rate and the ozone concentration in the duct. In a real in-duct air purifier, the effects of in-duct filters and outdoor ozone should also be considered.

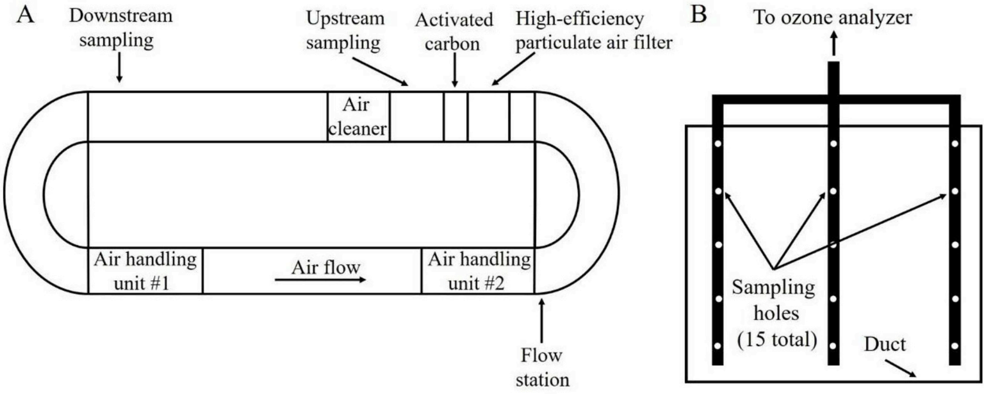

Fig. 5. Closed-loop chamber system for in-duct air cleaner (A) and sampling grid configuration (B).

3.3.2. *Calculation by single-zone mass-balance steady-state model*

The OER cannot be calculated directly for indirect testing. Hence, most investigations established the mass conservation equation [Eq. (5)] to obtain the OER. To ensure the accuracy of the OER calculation, some factors of the testing environment need to be considered in the mass conservation equation, as shown in Fig. 6. The mass-balance equation for determining the OER depends on the indoor ozone concentration, outdoor ozone concentration, air change rate, ozone penetration factor, and total removal rate of indoor ozone. For the single-zone mass-balance model, the OER of IOEDs can be quantified as

$$\frac{dC_{in}}{dt} = \frac{E}{V} + P\cdot\lambda\cdot C_{out} - \lambda C_{in} - \Sigma k C_{in} \tag{5}$$

The outdoor ozone concentration is generally measured before the test. The air change rate λ can be computed by fitting the decay curve of a CO_2/SF_6 tracer gas. There is usually no penetration in an airtight chamber. The value of P can also be estimated in the field (it is 0.8 in Ref. [19] and 0.52 in Ref. [24]). The indoor ozone concentration should be measured under the well-mixed environment. If the indoor ozone concentration reaches the steady state, during testing ($dC_{in}/dt = 0$), the equilibrium concentration of ozone, C_e (mg/m^3), can be monitored by an ozone analyzer, and Eq. (5) is modified as

$$E = (\lambda C_e + \Sigma k C_e - P\cdot\lambda\cdot C_{out})\cdot V \tag{6}$$

Eq. (6) shows the basic formula for the single-zone steady-state model. In the actual test experiment, Eq. (6) needs to be modified according to the conditions. If the test is operated in a well-sealed environment (which can be verified through the air tightness test, as described in ISO 16000-9 [77]) or ignore the impact of outdoor ozone, Eq. (6) can be simplified to Eqs. (7) and (8), as demonstrated in investigations by Britigan et al. [10] and Tuomi et al. [27], to calculate the OERs of various household and office devices, such as pet brushes, room air purifiers, car air purifiers, laser printers, and photocopiers. Unlike Eq. (6), Eqs. (7) and (8) do not require that the outdoor ozone concentration and penetration factor be determined. Eq. (7) does not even require measurement of the air exchange rate. The physical parameters that need to be measured can be reduced by changing the experimental conditions, which can avoid measurement errors in the test process.

$$E = \Sigma k\cdot C_e\cdot V \tag{7}$$

$$E = (\lambda C_e + \Sigma k C_e)\cdot V \tag{8}$$

In addition, when the device is turned off, we can use an "E-free" equation based on Eq. (6), and we can solve Eq. (9) to obtain the OER

Table 3
Equations used to calculate the OER in published literature.

Model	Calculation equation	Main parameters	Devices	Reference
Direct algebraic computation	Eq. (1)	Q, $C_{in-duct}$	Portable air cleaner	[12,14]
	Eq. (2)	Q, $C_{downstream}$	In-duct air cleaner	[19,79]
	Eq. (4)	Q,$\gamma_{filt} = 0.2$	In-duct air cleaner	[30]
Single zone model (steady state)	Eq. (6)	λ^{a}, $\Sigma k = 0$	Portable air cleaner	[28]
	Eq. (8)	λ, Σk^{a}	Portable air cleaner	[18]
	Eq. (8)	Q= 11.3m^3/h, $\Sigma k \in [2.3, 6.9]$	Laser printer & photocopier	[27]
	Eq. (7)	Σk	Portable/Wearable/Car air cleaner & Pet brush	[10]
	Eq. (8)	λ= 0.5, Σk = 4	Portable air cleaner	[29]
	Eq. (6)	λ, Σk, P= 0.52	In-duct air cleaner	[24]
	Eq. (6) & Eq. (9)	λ, Σk	In-duct air cleaner	[19]
	Eq. (9)	λ, Σk	Portable air cleaner	[13]
	Eq. (12)	λ, $\Sigma k = k_d + k_h$, $\gamma_{filt} = 0.2$	In-duct air cleaner	[30]
Single zone model (transient)	Eq. (14)	λ, $C_{in}(t)$	Photocopier	[16]
	Eq. (15)	Σk, $C_{in}(t)$	Portable air cleaner	[20,21]
	Eq. (19)	λ, M_i	Portable air cleaner	[22]
	Eq. (20)	$\frac{dC_{in}}{dt}$	Portable/Wearable/Car air cleaner & Pet brush	[10]
	Eq. (21)	λ, Σk, P	Shoe sanitizer & Facial steamer	[32]
	Eq. (5)	$\frac{dC_{in}}{dt}$, λ, Σk	Wearable air cleaner	[25]
Two zone model	Eq. (24) & Eq. (25)	λ, M	Portable air cleaner	[31]

[a] If there is no special statement in above published literature, the calculation of λ and Σk parameters in this article adopts the following formula by default.

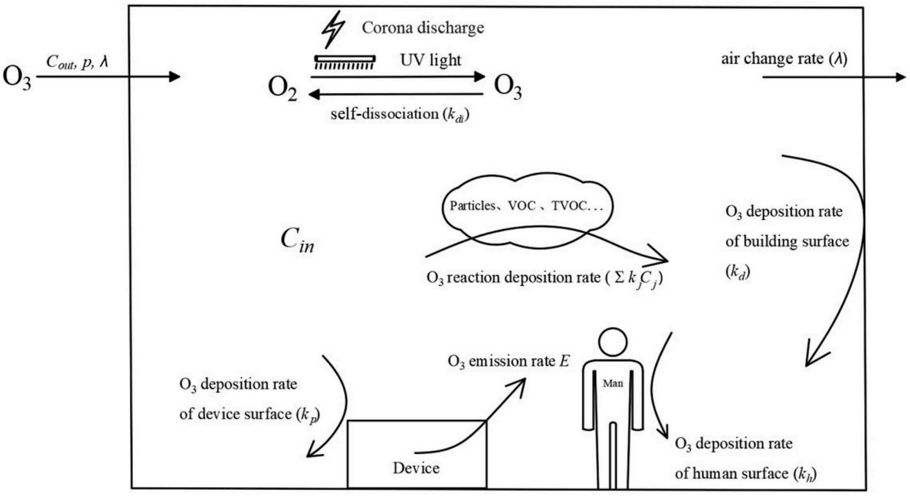

Fig. 6. Schematic illustration of indoor ozone generation and decay.

by subtracting the "E-free" equation from Eq. (6) and performing mathematical conversion. Eq. (9) does not require measurement of the outdoor ozone concentration and penetration factor, but it does require determination of the indoor ozone concentration when the device is turned off.

$$E = (\lambda + \Sigma k)\cdot(C_e - C_{\text{off}})\cdot V \tag{9}$$

After the IOED is switched off, the total indoor decay rate of ozone, R (the sum of Σk and λ), can be obtained from the ozone concentration decay curve. Then, Σk is obtained by subtracting λ from the total indoor decay rate, R. The total ozone removal rate Σk generally includes the removal rates of the indoor surfaces, human surfaces, and tested device surfaces, and the absorption of indoor air [45–48,69–74], as illustrated in Fig. 6 and Eq. (10).

$$\Sigma k = k_d + k_h + k_p + k_a = \Sigma\frac{\nu_d\cdot A}{V} + \Sigma\frac{\nu_h\cdot A_h}{V} + \Sigma\frac{\nu_p\cdot A_p}{V} + (\Sigma k_j C_j + k_{di}) \tag{10}$$

Because of uncertainties in the experimental environment and conditions, the ozone removal factors need to be considered according to the actual conditions during testing. If the filters of the in-duct air purifier are taken into account and only the ozone removal by human surfaces is considered [30], Eq. (5) becomes

$$\frac{dC_{in}}{dt} = (1 - \gamma_{\text{filt}})\cdot\frac{E}{V} + \lambda(1 - \gamma_{\text{filt}})C_{\text{out}} - \lambda C_{\text{in}} - k_d C_{\text{in}} - k_h C_{\text{in}} \tag{11}$$

When the ozone concentration does not change over time, the solution for Eq. (11) is

$$E = \frac{[(\lambda + k_d + k_h)\cdot C_e - (1 - \gamma_{filt})\cdot\lambda\cdot C_{out}]\cdot V}{(1 - \gamma_{filt})} \tag{12}$$

3.3.3. Calculation by single-zone mass-balance transient model

If the indoor ozone concentration cannot reach the steady state. during the testing time ($dC_{in}/dt \neq 0$) [24], the transient indoor ozone concentration, which is the integral of the concentration over time in Eq. (5), needs to be quantified using Eq. (13):

$$C_{in}(t) = \left(C_{in(0)} - \frac{\lambda PC_{out} + \frac{E}{V}}{\lambda + \Sigma k}\right)e^{-(\lambda + \Sigma k)t} + \frac{\lambda PC_{out} + \frac{E}{V}}{\lambda + \Sigma k}$$
$$= C_{in(0)}e^{-(\lambda + \Sigma k)t} + \frac{\left[\lambda PC_{out} + \frac{E}{V}\right]}{\lambda + \Sigma k}(1 - e^{-(\lambda + \Sigma k)t}) \tag{13}$$

Using Eq. (13), Leovic et al. [16] presented Eq. (14) to obtain the OER of printing devices without considering the initial ozone concentration $C_{in(0)}$, outdoor ozone concentration C_{out}, and total ozone removal rate Σk. They considered that, under their experimental conditions, the required accuracy for calculating the OER of printing devices can still be met when these three physical parameters are neglected if the values of these parameters are small. Because the experimental environment was well-sealed, Niu et al. [20,21] considered the OER of air purifiers to depend only on the ozone removal rate in a defined space [see Eq. (15)]. Both Eqs. (14) and (15) are used in regression analyses of measured concentration data to obtain the OER.

$$C_{in}(t) = \frac{E_p}{\lambda\cdot V}(1 - e^{-\lambda\cdot t}) \tag{14}$$

$$C_{in}(t) = \frac{E}{\Sigma k\cdot V}(1 - e^{-\Sigma k\cdot t}) \tag{15}$$

In contrast, Tung et al. [22] calculated the OER by obtaining the initial slope of the ozone concentration growth curve after the IOED was turned on. There was unity penetration ($P = 1$), and only the total ozone removal rate Σk in the test chamber was taken into account. The equilibrium ozone concentration C_e when the device ran for an infinite amount of time could be expressed as Eq. (16), which is based on Eq. (13). Then, Eq. (13) can be rewritten as Eq. (17). By setting the differential of Eq. (17) with respect to time, t, to zero, instead of solving the decay parameters ($k_d + k_p + \Sigma k_j C_j + \lambda$) directly, the initial slope of the ozone growth curve, M_i, can be obtained using Eq. (18), which is based on Eq. (17). By substituting Eq. (18) into Eq. (16) and rearranging the equation, Eq. (19) for the OER of air purifiers is obtained. Practically, the accuracy of the OER is associated with the initial slope, M_i.

$$C_e = \frac{\lambda\cdot P\cdot C_{out} + \frac{E}{V}}{\lambda + \Sigma k} = \frac{\lambda C_{out} + \frac{E}{V}}{k_d + k_p + \Sigma k_j C_j + \lambda} \tag{16}$$

$$C_{in}(t) = (C_{in(0)} - C_e)e^{-(k_d + k_p + \Sigma k_j C_j + \lambda)t} + C_e \tag{17}$$

$$\left.\frac{dC_{in}}{dt}\right|_{t\to 0} = -(k_d + k_p + \Sigma k_j C_j + \lambda)(C_{in(0)} - C_e)e^{-(k_d + k_p + \Sigma k_j C_j + \lambda)t}|_{t\to 0}$$
$$= M_i \tag{18}$$

$$E = \left[\frac{V\cdot M_i}{C_e - C_{in(0)}}\right]\cdot C_e - \lambda\cdot V\cdot C_{out} \tag{19}$$

Britigan et al. [10] also used the law of linear increase of the ozone concentration in a Teflon bag to obtain the slope so as to calculate the OER. If the test is performed in a well-sealed environment, such as a Teflon bag, and the ozone removal is negligible, the second, third, and fourth terms on the right-hand side of Eq. (5) can be ignored, and Eq. (5) can be simplified as

$$E = \frac{\mathrm{d}C_{\mathrm{in}}}{\mathrm{d}t}\cdot V \tag{20}$$

The advantage of Eq. (20) is that the OER of many devices can be obtained in a short time. However, strict control is needed during the experiment to avoid large errors. In particular, the method of Zhang & Jenkins [32] can also be used to test the OER of many devices in a short period of time. To compare the ozone emission of 17 different types of household appliances, they proposed using the OER of an IOED within the period of one use cycle. By rearranging Eq. (5) and integrating all the terms over the period of one use cycle, the average OER over one use cycle, $\int_0^T E\mathrm{d}t/T$, is defined as

$$\frac{\int_0^T E\mathrm{d}t}{T} = \frac{V(C_{\mathrm{in}(T)} - C_{\mathrm{in}(0)})}{T} - P\cdot\lambda\cdot V\cdot C_{\mathrm{out}} + \frac{V(\lambda + k)}{T}\int_0^T C_{\mathrm{in}}\mathrm{d}t \tag{21}$$

where $\int_0^T C_{\mathrm{in}}\mathrm{d}t$ is estimated as $\sum_1^i[(C_{\mathrm{in(n-1)}} + C_{\mathrm{in}(n)})/2]\Delta t$, $C_{\mathrm{in}(n-1)} + C_{\mathrm{in}(n)}$ is the sum of two adjacent data points of C_{in}, Δt is the time interval between two data points, and i is the total number of data points.

3.3.4. Calculation by two-zone mass-balance model

Yu et al. [31] established the dynamic ozone mass-balance model of both indoor and internal wall surfaces, which differs from the single-zone model. They proposed Eqs. (22) and (23), which include factors for ozone adsorption, desorption, and deposition, to quantify the actual OER of ion air purifiers. The adsorption, desorption, and deposition rate constants of ozone were obtained by fitting a nonlinear regression curve based on the experimental data for the variation in ozone concentration. The effective ozone emission rate, E_{eff}, was quantified by solving the discrete forms of Eqs. (22) and (23), which are expressed as Eqs. (24) and (25), respectively.

$$\frac{\mathrm{d}C_{\mathrm{in}}}{\mathrm{d}t} = \frac{E}{V} + \lambda C_{\mathrm{supply}} + k_{\mathrm{D}}\cdot\frac{A}{V}\cdot M - \lambda C_{\mathrm{in}} - \mathrm{k_a}C_{\mathrm{in}} - \frac{\lambda_0\gamma_{\mathrm{filt}}F}{V}C_{\mathrm{in}} \tag{22}$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = k_{\mathrm{a}}\cdot\frac{V}{A}\cdot C_{\mathrm{in}} - (k_{\mathrm{D}} + k_{\mathrm{r}})M \tag{23}$$

$$E_{\mathrm{eff}}\left(t = \frac{t^n + t^{n+1}}{2}\right) = V\left[\frac{c_{\mathrm{in}}^{n+1} - c_{\mathrm{in}}^n}{\Delta t} + (\lambda + k_{\mathrm{a}} + k_{\mathrm{r}})\frac{c_{\mathrm{in}}^{n+1} + c_{\mathrm{in}}^n}{2} - k_{\mathrm{D}}\cdot\frac{A}{V}\cdot\frac{M_{03}^{n+1} + M_{03}^n}{2} - \lambda C_{\mathrm{supply}}\right] \tag{24}$$

$$M^{n+1} = \frac{\frac{k_{\mathrm{a}}\cdot\frac{V}{A}\cdot\Delta_t(C_{\mathrm{in}}^{n+1} + C_{\mathrm{in}}^n)}{2} + \frac{(2 - k_{\mathrm{D}}\Delta_t)M^n}{2k_{\mathrm{D}}\Delta t}}{2 + \mathrm{k_D}\Delta\mathrm{t}};\ n = 0,\ M = 0\left(\text{this was derived from } \frac{M^{n+1} - M^n}{\Delta t} = k_a\cdot\frac{V}{A}\cdot\frac{C_{\mathrm{in}}^{n+1} + C_{\mathrm{in}}^n}{2} - k_{\mathrm{d}}\frac{M^{n+1} + \mathrm{M^n}}{2}\right) \tag{25}$$

Eqs. (24) and (25) have the advantage of being more comprehensive than the single-zone model, but using them increases the possible experimental error during testing because it is necessary to assess the ozone adsorption and desorption.

Air change rate: $\lambda = \frac{\mathrm{I_n}(\mathrm{C_{g(t2)}} - \mathrm{C_{g(b)}}) - \mathrm{I_n}(\mathrm{C_{g(t1)}} - \mathrm{C_{g(b)}})}{\mathrm{t_2} - \mathrm{t_1}}$;

Total indoor decay rate: $\mathrm{R} = \frac{\mathrm{I_n}(\mathrm{C_{in(t2)}} - \mathrm{C_{in(b)}}) - \mathrm{I_n}(\mathrm{C_{in(t1)}} - \mathrm{C_{in(b)}})}{\mathrm{t_2} - \mathrm{t_1}}$;

Total ozone removal rate: $\Sigma\mathrm{k} = \mathrm{R} - \lambda$, $\Sigma\mathrm{k} = \mathrm{k_d} + \mathrm{k_h} + \mathrm{k_p} + \mathrm{k_a}$.

4. Emission rate of different indoor ozone sources

IOEDs studied in the literature include photocopiers, laser printers, room ion purifiers, car ion purifiers, wearable air purifiers, pet brushes, in-duct air cleaners, ozone generators, fruit and vegetable washers, and shoe sanitizers. The OERs of various IOEDs presented in the literature [10,11,13–25,27–33] are summarized in Figs. 7 and 8. The mean value of the OER is chosen if there are multiple sets of experiments for the same device in one study. The data are divided into six groups: in-duct air cleaners, ozone generators (including fruit and vegetable washers and shoe sanitizers), room air purifiers, photocopiers, laser printers, and others. The last group includes small and portable devices such as car ion purifiers, pet brushes, and wearable air purifiers. As shown in Figs. 7 and 8, the OER of the IOEDs ranges between 34 μg/h and 344 mg/h, covering four orders of magnitude. The highest OER is that of in-duct air cleaners tested in a chamber, and the lowest OER is that of wearable air purifiers.

Figs. 7 and 8 illustrate that the average OERs of in-duct air cleaners, ozone generators, room air purifiers, photocopiers, laser printers, and other small devices are 62.8, 76.3, 4.6, 3.3, 0.8, and 0.4 mg/h, respectively. The OERs of in-duct air cleaners and ozone generators are generally larger than those of photocopiers and printers. The highest OER of a room air purifier is 30.5 mg/h, whereas the lowest is 56 μg/h. The maximum is approximately 550 times the minimum, which indicates differences in the OER for the same type of room air purifier. The average OER of photocopiers is higher than that of printers. In addition, the maximum and minimum OERs of photocopiers and printers differ by approximately 20 times and 40 times, respectively. The average OERs obtained from field testing and environmental chamber testing of in-duct air cleaners, ozone generators, and room air purifiers differ by 50%, 15%, and 0.3%, respectively. According to the data, there is almost no difference in the OERs of room air purifiers obtained by field tests and chamber tests. However, the average OER of in-duct air cleaners was half the difference between the values obtained in the

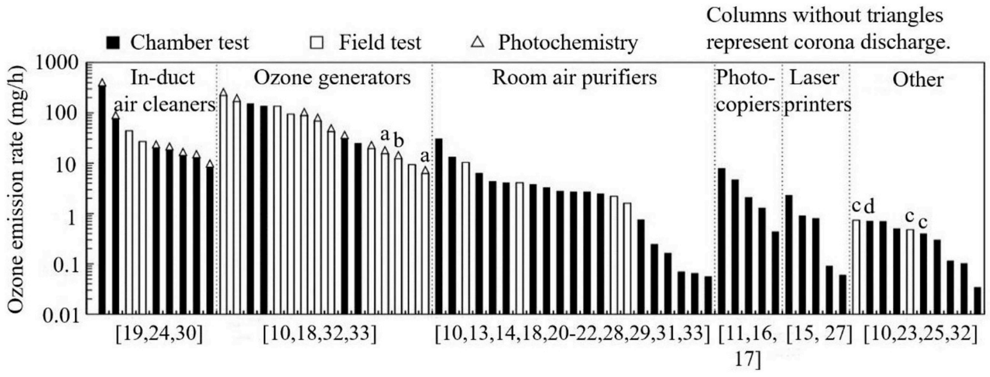

Fig. 7. OERs of IOEDs presented in the literature [10,11,13–25,27–33]. Mean value of the OER is chosen if there are multiple sets of experiments for the same device in one investigation. a: fruit and vegetable washers, b: shoe sanitizers, c: car (dashboard) ionizer purifiers, d: pet brushes. Other data in the “Other” group are for wearable air purifiers.

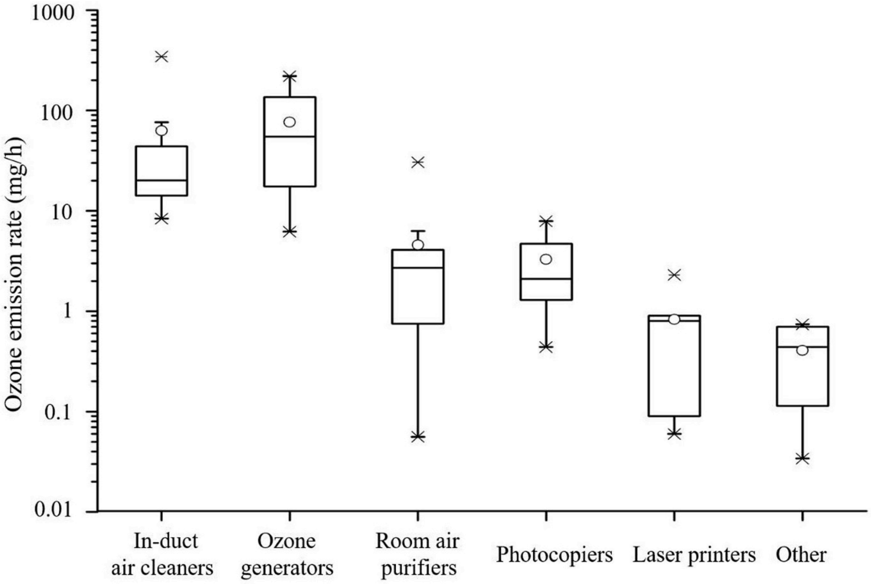

Fig. 8. OERs of IOEDs presented in the literature [10,11,13–25,27–33]. Mean value of the OER is chosen if there are multiple sets of experiments for the same device in one investigation. In each box, the mid-line shows the median value, the top and bottom of each box show the upper and lower quartiles (the 75th and 25th percentiles), and the upper and lower whiskers represent the 90th and 10th percentiles, respectively. Mean values are represented by rectangular points, and extreme values are drawn as fork points.

two test environments. Therefore, it can be speculated that the mechanism of ozone generation strongly influences the OER of in-duct air cleaners, because in the literature, all of the in-duct air cleaners examined in a chamber use the photochemical mechanism, whereas the in-duct air cleaners examined by field testing operate by corona discharge. When ozone generators were tested in the two environments, the difference in the OER was found to be 15% (approximately 11.5 mg/h in absolute value). Moreover, the OERs of ozone generators operating by the photochemical and corona discharge mechanisms were 6.2–220 and 9.4–151 mg/h, respectively. This illustrates that ozone generators have a wider numerical range and maximum peak value when operated by the photochemical mechanism. In addition, although some household devices, such as car ion purifiers, pet brushes, and wearable air purifiers, have lower OERs, these devices still need more attention. These portable devices can emit ozone directly into the breathing zone of the human user and increase the ozone exposure.

The ozone emission per unit paper of printers and photocopiers obtained by considering the printing speed or printing time are shown in Fig. 9A [11,15–17,27]. The ozone emission per kilowatt hour obtained by considering the energy consumption is shown in Fig. 9B [10,13,18,19,23–25,29,32]. In Fig. 9A, the average ozone emission per unit paper for laser printers and photocopiers is 0.1×10^{-2} and 1.37×10^{-2} mg/copy, respectively. The ozone emission per unit paper for photocopiers is approximately one order of magnitude higher than that of laser printers, whereas the OER of photocopiers is approximately four times that of laser printers. As shown in Fig. 9B, the mean values of ozone emission per kilowatt hour for in-duct air cleaners, ozone generators, room air purifiers, and other devices are 2.9, 4.1, 0.3, and 7.4 g/(kW·h), respectively. Compared with the OERs shown in Fig. 8, the ozone emission per kilowatt hour and OER of most ozone generators are both larger than those of most in-duct air cleaners, indicating that ozone generators emit ozone more efficiently than in-duct air cleaners in terms of emission rate and power consumption. The OER and ozone emission per kilowatt hour of room air purifiers are both lower than those of ozone generators and in-duct air cleaners. The mean ozone emission per kilowatt hour for the Other group is highest and has the widest range, indicating that the power consumption of devices in the Other group, such as car ion purifiers, pet brushes, and wearable air purifiers, is comparatively large. The higher power consumption and direct impact of the pollution in the human breathing zone of these devices require serious consideration.

Some studies measured the emissions of other contaminants by the devices in addition to ozone, as shown in Table 4. VOCs, PM, formaldehyde, acetaldehyde, and NO_x were detected [11,13,15,16,18,24,27,29,30,97]. Note that laser printers and photocopiers also generate considerable heat, which increases the pollutant emission during operation. The clean air delivery rate of room air purifiers was measured, but no pronounced correlation was found between the clean air delivery rate and OER [25,29].

5. Factors influencing ozone emission

In reported tests of the OER of IOEDs, some factors could affect the numerical value of the OER. These include the design and operational conditions of the IOED, the environmental conditions in which the IOED is tested, and the data analysis method used.

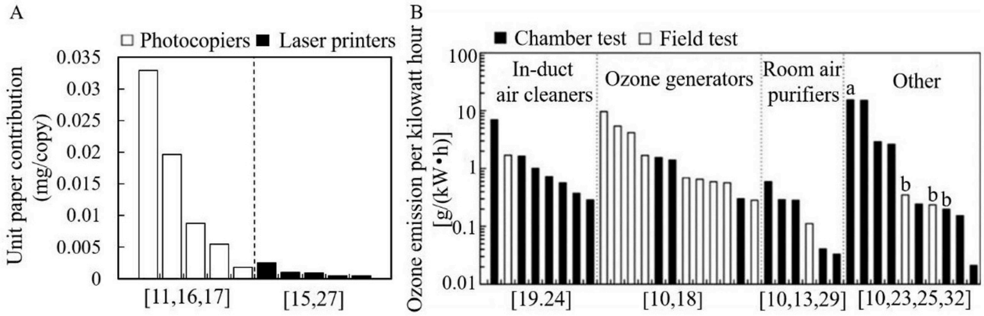

Fig. 9. Ozone emission per unit paper (A) and per kilowatt hour (B) [10,11,13,15–19,23–25,27,29,32]. Mean value of the OER is chosen if there are multiple sets of experiments for the same device in one investigation. a: pet brushes, b: car (dashboard) ionizer purifiers. Other data in the "Other" group represent wearable air purifiers.

Table 4
Monitoring of other contaminants emitted by IOEDs.
[a] "+" represents other pollutants monitored in the published literature.

Device	VOCs	Particles	Others	Reference
Laser printer	+[a]	+		[15]
Laser printer	+		Formaldehyde	[27]
Laser printer	+	+		[97]
Photocopier	+	+	Formaldehyde, NO_2	[11]
Photocopier	+		Formaldehyde; Acetaldehyde	[16]
Room air purifier	+	+	Formaldehyde; Acetaldehyde	[13]
Room air purifier	+	+	Formaldehyde; Acetaldehyde	[29]
In-duct air cleaner		+		[24]
In-duct air cleaner		+		[30]
Ozone generator			NO_x	[18]

5.1. Impact of device design and use on ozone emission rate

The OER depends mainly on the IOED itself and the user behavior patterns. Some previous studies discussed the impact of IOED design and use on the OER; they covered the structure and material of the corona electrode, working current and voltage of the device, characteristics of the UV lamps, airflow rate setting of air purifiers, cleaning setting of disinfectors and air cleaners, printing speed of printing devices, routine maintenance of air cleaners, etc.

5.1.1. Impact of device design on ozone emission rate

For devices that use the corona discharge mechanism, Castle et al. [82] and Viner et al. [28] found that the radius of curvature of the electrode is the key factor determining the OER, and a small-diameter wire consumed a certain amount of ozone. Boelter & Davidson [90] confirmed that reducing the wire's diameter as much as possible while guaranteeing its durability was conducive to reducing ozone production. Liu et al. [89] and Bo et al. [65,66] also proved that the OER increased with increasing wire diameter and number of holes on the grounded screen and with decreasing electrode spacing between the discharge wire and grounded screen. The material, type (tuft or glow), and polarity (positive or negative) of the corona electrode all affect the OER [28,64,80–82,85,86,89]. Boelter & Davidson [90] measured the OER of four wire materials and found that the OER decreased in the following order under both positive and negative polarity: titanium > tungsten > copper > silver. Liu et al. [89] also found that an ion air purifier with gold wires has a higher OER than a purifier with silver wires. Durme [64], Hegeler [67], Ma [85], Cooray [86], Boelter & Davidson [90], and Huang et al. [93] all observed higher ozone generation for positive corona discharge than for negative corona discharge.

The working current and voltage of IOEDs are also important factors affecting ozone emission. Boelter & Davidson [90] reported a lower OER when an ion air cleaner was operated at the lowest current level. Shi et al. [25] found that an ion air purifier with metallic corona discharge has a higher OER than an ion air purifier that uses a carbon fiber ionizer for ion generation, because a carbon fiber ionizer typically requires a lower voltage than the metallic cathodes used for corona discharge to reach the same level of ionization. Lee et al. [15] found that a printing device operating at high voltage has a high OER by testing five printing devices: two laser printers operated at 374 and 408 W, which had average OERs of 1.2 and 1 μg/copy, respectively, and two inkjet printers and one all-in-one (color printer, fax, copier, scanner) printing device operated at voltages of 12, 12, and 15 W, respectively, which had an average OER of 0.1 μg/copy. Further studies have confirmed that increasing the corona current and discharge voltage clearly increases ozone generation [65,66,89,90,93]. However, the effect of increasing the corona current on ozone emission and the effect of suppressing the wire surface temperature on ozone production are mutually reinforcing. Hence, the corona current and corona wire surface temperature have a trade-off effect on ozone production.

For devices operating by the photochemical mechanism, ozone production is directly related to the power of the UV lamp and increases with increasing power. However, the efficiency of mercury lamps for converting electric energy into radiation energy at a wavelength of 185 nm ranges from 0.6% to 1.5% [55]. Therefore, the conversion efficiency of the lamp also affects ozone generation. The material and size of the tube or reaction chamber in which the UV lamp is located also affect ozone generation. For example, avoiding the use of polished aluminum plates and other reflective materials can increase the absorption of UV rays on the chamber surface and reduce ozone generation, and reducing the size of the tube or chamber can increase heat accumulation, enhancing ozone decomposition [55]. In addition, introduction of a catalyst such as Mn/ZSM-5 or Au/TiO_2 can also increase the ozone degradation efficiency [51,54].

5.1.2. Impact of device use on ozone emission rate

In addition to the design factors of the IOED itself, the operating mode and level set by users can also affect the OER, for example, the airflow rate of air purifiers, printing speed and mode of printing devices, and cleaning level of disinfectors. Whether the user maintains and cleans an IOED regularly can also affect its OER.

According to theoretical research on the corona discharge mechanism, increasing the oxygen content of the gas source causes a nonlinear increase in ozone production [55]. At a certain corona power, the ozone yield increases with increasing gas supply. However, as shown in Fig. 10, OER measurement of actual air purifiers showed that the behavior of only a few air purifiers, such as the No. 10 Air-Zone AIR Duct 2000 [19], was clearly consistent with the theoretical research findings. In some studies [12,19,79], the ozone emission strength of an air cleaner was independent of the airflow. Viner et al. [28] found that the air velocity generally has little impact on the OER. Mason et al. [18] recognized that the OER is not particularly sensitive to airflow. As shown in Fig. 10 by the variation of the column height (the OER of air cleaners), no specific relationship appeared between the airflow rate and OER for most air purifiers. Under actual conditions, the structural design and material selection of different brands of air purifiers are different, and the ozone removal effect of different filter elements also varies. Many uncertainties make it difficult to control the airflow rate as a single variable affecting ozone emission, so it is difficult to reach a consistent conclusion. The reasons need to be further explored in detail.

The average OERs of fruit and vegetable washers were 15.4 and 14.4 mg/h for the high and low cleaning settings, respectively [32]. The OERs of three air purifiers, namely, the portable air purifiers Sharper Image Ionic Breeze (with germicidal protection), Sharper Image Ionic Breeze Quadra Pro, and Sharper Image Ionic Breeze Quadra Compact [14], are higher at high settings than at low settings. Hence, existing research indicates that the OER increases at higher cleaning settings. Compared to the air purifier flow rate and disinfector strength, the working conditions of printing devices had more diverse effects. The OER of printing devices was affected to varying degrees by the material and size of the paper used, whether the inkjet was black or color, the coverage of the sheet surface, and whether single-sided or double-sided printing was used [11]. Unfortunately, very little research has been done on how these factors affect the ozone emission of printing devices. Valuntaite & Girgzdiene [61] found that the OER of printing devices increased significantly with increasing printing speed.

Furthermore, user behavior and habits can also influence the OER of some IOEDs. Emmerich & Nabinger [91] reported that ozone production is reduced by decreasing the operation time and ensuring correct installation. The OER of ion air cleaners can be reduced by routine cleaning and maintenance, likely because of enhanced ozone removal resulting from replacement of aging filters [16,27,31,92]. Zuraimi et al. [60] and Huang et al. [93] found that dust led to decreased ozone generation by ESPs, possibly owing to forced decreases in the corona current. However, Bowser [94] tested 10 ESPs and did not find a

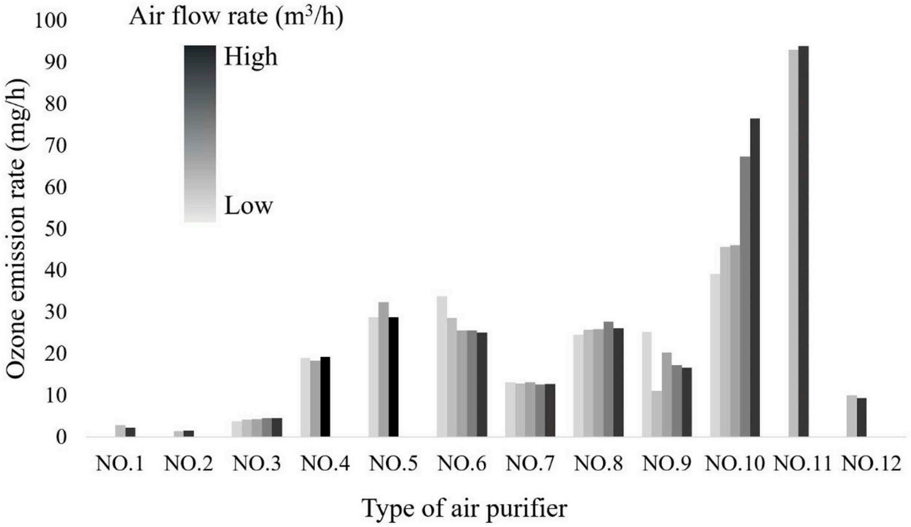

Fig. 10. Variation in OER with the airflow rate of air cleaners. No. 1 to No. 12 on the abscissa represent portable air purifier #6 in Ref. [31], the portable air purifier Oreck Super Air 8 in Ref. [14], in-duct air cleaners #1, #2, #5, and #7 in Ref. [79], the Guardian Air by RGF #2, Honeywell F300 Electronic Air Cleaner, activTek INDUCT 2000 #2, and Air-Zone Air Duct 2000 #2 in Ref. [19], and the portable indoor air cleaners XL-15 and Biozone 500 in Ref. [12], respectively. The airflow rate in the figure is relative to the flow of the air purifier itself.

specific relationship between ozone production and cleaning, as some showed an increase, some showed a decrease, and some showed no appreciable change after cleaning. In addition, there is no meaningful relationship between the change in the cell and screen mass of the ESP and ozone production before and after cleaning. Further research is needed to determine whether periodic cleaning and maintenance affect the OER of different types of IOED.

5.2. Impact of environmental conditions on ozone emission rate

Environmental conditions such as temperature, RH, and test site may cause variations in OER monitoring. According to Table 1, the temperature in most experimental studies ranged from 20 to 35 °C. Morrison et al. [19] and Morent et al. [87] found that the OERs of IOEDs were lower at higher ambient temperatures. Boelter & Davidson [90] found that as the air temperature of electrostatic air cleaners was increased from 20 to 28 °C, the ozone production dropped by 6%. By heating the corona wire surface of a negative ion generator, Liu et al. [89] found that heating the corona wire can directly suppress ozone formation. Most published studies [10,18,28,64,66,87,89,90] found that increasing the RH reduces the OER of IOEDs using the corona discharge mechanism. The reason may be that water molecules react with atomic oxygen radicals to form ozone-depleting hydroxyl groups, thereby improving the ozone removal capacity [28,64,84]. However, Morrison et al. [19] could not obtain a clear relationship between the RH and OER by changing the air humidity of an in-duct air cleaner. Peyrous et al. [83] also found ozone generation to be independent of RH for positive corona devices over the range of 20%–80% RH. By experimentally measuring the OER of a DC-energized ESP, Viner et al. [28] confirmed that water vapor interacts with a negative corona discharge to reduce ozone production, whereas the OER of positive corona discharge was independent of RH. Boelter & Davidson [90] also found that both the temperature and humidity of air can affect ozone production, but not very strongly.

According to the OER shown in Fig. 7, no clear conclusion can be reached about the impact of chamber or field testing of each type of device. Bowser [94] found no significant correlation between the OER of six groups of ESPs and the indoor and outdoor background ozone concentrations. These uncertainties result mainly from numerous interfering factors, such as the presence of PM and organic matter, temperature, RH, light, and air penetration [30], in field testing. Increasing the ambient temperature and humidity can usually limit ozone generation by IOEDs. It is well known that ozone can react with unsaturated organic compounds, which are produced mainly by indoor household electrical appliances, building materials, smoking, and cooking, and are decomposed by sunshine outdoors [64]. The outdoor ozone concentration is typically greater than the indoor ozone concentration [94]. The uncertainty of outdoor air infiltration will affect measurement of the indoor ozone concentration and thus affect assessment of the OER of IOEDs. Although the decay constant can be obtained by monitoring emission before or after the test, this procedure cannot guarantee that these interfering factors will not change over time, causing the OER of IOEDs to vary during field testing. Owing to uncertainties in the testing environment in the field, it is difficult to determine how the measured OER of IOEDs is affected by whether field or chamber testing is performed. That is, chamber tests more accurately reflect the true OER of IOEDs under good control, and field tests are more useful for evaluating how harmful the OER is to humans.

5.3. Impact of data analysis process on ozone emission rate

Some previous investigations have adopted different data analysis processes under the same experimental conditions. To assess the impact of using different data analysis processes on the OER of IOEDs, 6 groups of ion air purifiers and 11 groups of in-duct air cleaners investigated under the same working conditions in six studies [19–22,30,31] were selected as samples for comparison.

To obtain the OER of the ion air purifiers in chamber tests, Niu et al. [20,21], Tung et al. [22], and Yu et al. [31] adopted the nominal ozone emission rate method (NEM), initial slope method (ISM), and effective ozone emission rate method (EEM), respectively, where we assigned the names for these processes that we use in this paper. The three calculation processes are described in section 3.3 on data analysis. Here, we compare the results calculated using the ISM and EEM with those obtained by the NEM. As shown in Fig. 11, two different sets of air purifiers were used to compare the results of the NEM and ISM (No. 1–3) and the results of the NEM and EEM (No. 4–6). The dark gray, medium gray, and light gray bars represent the calculated ISM, EEM, and NEM results, respectively.

The maximum absolute error of the OER between the ISM and NEM was 0.6 mg/h, and the smallest absolute error of the OER was only 21 μg/h. Although the monitored OER was small in terms of the absolute numerical value, the relative numerical values showed a more significant difference. The relative values relative to the average values for the ISM were 12.5%, 4.2%, and 6.6% lower than those calculated by the NEM. If we substitute the algebraic formula for M_i into Eq. (19), we obtain the form in Eq. (6). Compared with Eq. (15), the ISM considers more items associated with ventilation of the chamber, and the analysis results indicate that the indoor ozone outflow is not as significant as the outdoor ozone inflow. Note also that, unlike the NEM, the ISM does not

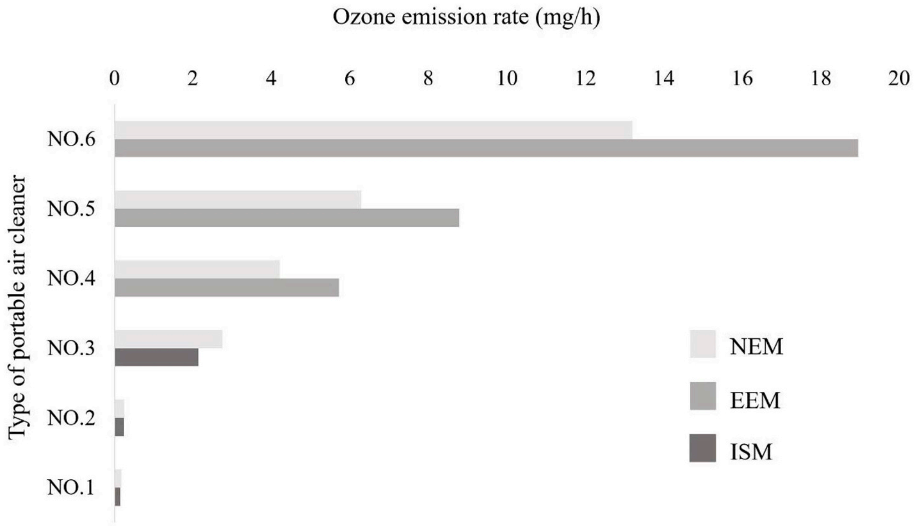

Fig. 11. OERs of portable air cleaners calculated by three processes. The NEM and ISM results of three groups of air purifiers were compared in Refs. [20–22], and the NEM and EEM results of three other groups of air purifiers were compared in Ref. [31].

require solution of the ozone removal rate Σ*k*. That is, even though the tested devices, experimental environment, and testing process were identical, the possibility that the performance of the tested devices changed between the two tests could not be ruled out. In any case, from the results of the current study, the values calculated using the NEM are always slightly higher than those calculated using the ISM.

In contrast to the study described above, Yu et al. [31] found that the relative values obtained by EEM analysis were 17.9%, 16.6%, and 15.1% higher than those obtained using the NEM, respectively. The maximum absolute error of the OER was 5.8 mg/h, surprisingly, and the smallest absolute error of the OER was 1.5 mg/h. We found a large variation between the OER results obtained by the EEM and NEM. Although both methods consider the ozone absorption of the filters, the EEM is specialized to model ozone removal more realistically., whereas the NEM is universal. However, this discrepancy might be explained by the fact that the difference in the ozone decay rate constant in the two-zone model estimated by the EEM was higher than the Σ*k* value of the single-zone model obtained by the NEM.

Morrison et al. [19] monitored 10 in-duct air cleaners and did not observe an obvious relationship between the OERs calculated using Eqs. (6) and (9). As shown in Fig. 12, the maximum absolute error between the results of the two equations was 9.8 mg/h (No. 9, AirZone Air Duct 2000), and the minimum absolute error was 0.7 mg/h (No. 3, activTek INDUCT 2000 #2). The largest differences between the relative values of the two equations were 15.9%, 15.1%, and 23.1% (No. 2, Trane Clean Effects and No. 4 and No. 3, activTek INDUCT 2000 #1 and #2, respectively), and the smallest differences between the relative values of the two equations were 1.6% and 1.1% (No. 11 and No. 10, HVAC UV 560 #1 and #2, respectively). Therefore, it can be concluded that when the absolute numerical value of the OER of an in-duct air cleaner is relatively large, the calculation results of the two equations will differ slightly, otherwise resulting in a large calculation error. Hence, when the OER of in-duct air cleaners is relatively small, one of the two modified equations should be selected cautiously according to the actual test conditions.

According to Eq. (12) of Xiang et al. [30], the computed average value of *E* was 23 mg/h when k_h had to be included in the equation during the occupied period and 25 mg/h when k_h could be neglected (in an unoccupied room). However, the *E* value calculated using Eq. (4) was 29 mg/h. According to Eq. (12), the mean error of 2 mg/h should

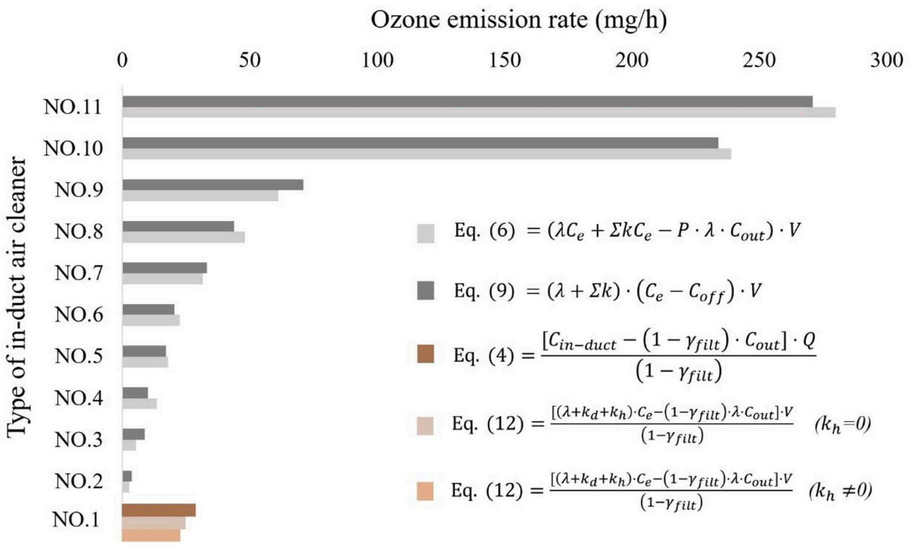

Fig. 12. OERs of in-duct air cleaners calculated by different data analysis processes [19,30]. No. 1 to No. 11 on the abscissa represent the in-duct air cleaner in Ref. [30] and Trane Clean Effects; activTek INDUCT 2000 #2 and #1; the Trane Catalytic Air Cleaning system; Honeywell F300 Electronic Air Cleaner #3, #2, and #1; AirZone Air Duct 2000; and HVAC UV 560 #2 and #1 in Ref. [19], respectively.

theoretically reflect the difference in whether the calculation includes the human surface deposition factor, and the formula including k_h would have given a larger value. However, this may in fact be due to variation in the RH of the air supplied in the two tests, according to an additional explanation by Xiang et al. That is, even if k_h was taken into account, the presence or absence of humans would have little effect on the obtained OER of in-duct air cleaners. In other words, the human body surface deposition factor has less effect on the calculated OER than the variation in the RH of the supplied air. The absolute numerical value of the OER calculated from Eq. (4), which was recommended by Xiang et al., was approximately 5 mg/h greater than that obtained using Eq. (12). The relative error of approximately 9.4% also indicates the OERs calculated by the two processes differed significantly. Because ozone removal by filters and outdoor ozone interference are both considered in the two equations, the natural decay of ozone indoors was the main reason for this error. Eq. (4) does not require consideration of the decay of ozone in the room, and the ozone production rate of the device could be obtained more directly and accurately. Nevertheless, the OER obtained using Eq. (12) is more realistic and more suitable for human exposure, but it is necessary to pay attention to ozone decay, especially under field test conditions.

The above discussion shows that assessment of the ozone removal rate is the main source of error in calculating the OER. However, direct algebraic computation can avoid the effects of ozone removal and is more suitable for obtaining the true OER of IOEDs. The OER obtained through the single-zone or two-zone model is inevitably affected by various ozone removal factors, but it is more useful for assessing the level of human exposure to the ozone emission. The strength of the effect of these removal factors varies; for example, the RH ozone removal effect is greater than the human surface effect, and the ozone decay rate of the two-zone model is higher than that of the single-zone model. Further exploration in actual test environments is necessary to determine whether these findings are universal, and further studies are needed to determine the strength of the effects of considering more ozone removal terms.

6. Summary

Office and household appliances can be significant sources of indoor ozone. Therefore, the OER of these IOEDs is crucial for evaluating indoor ozone concentrations and human exposure. Previous investigations found that the OERs of in-duct air cleaners, ozone generators, room air purifiers, photocopiers, laser printers, and other small devices range from 8.4 to 344 mg/h, 6.2–220 mg/h, 56 μg/h to 30.5 mg/h, 0.4–7.9 mg/h, 60 μg/h to 2.3 mg/h, and 34 μg/h to 0.74 mg/h, respectively, and the mean OERs of these devices are 62.8, 76.3, 4.6, 3.3, 0.8, and 0.4 mg/h, respectively. The OERs of in-duct air cleaners and ozone generators are generally larger than those of photocopiers and printers. The OER is determined mainly by the device itself, e.g., its working mechanism, internal structure, and materials. The average ozone emission per unit paper of photocopiers is larger than that of printers. The ozone emission per kilowatt hour values of pet brushes and wearable air purifiers are the highest, indicating that they emit the largest amount of ozone per unit of electricity among all the IOEDs studied. We have to be more prudent to purchase and use these devices in everyday life because they can emit ozone directly into the human user's breathing zone and increase the ozone exposure.

The OER of indoor sources depends mainly on the IOED itself and the user behavior, including the working mechanism, working current and voltage, operating mode and level setting, and routine maintenance. The OER can also be influenced by the test conditions such as temperature and RH. To some extent, the data analysis process can also affect the quantification of the OER. We found that the IOEDs investigated to date are mostly air purifiers, printers, photocopiers, and ozone generators, and there are few studies of the OER of other household and office IOEDs, such as electric irons, hair dryers, electric teapots, vacuum cleaners, and computers. In addition, there are fewer experimental data and a limited number of research articles on some IOEDs, such as wearable air purifiers, fruit and vegetable washers, and shoe sanitizers. Future studies are needed to determine the emission of ozone and other pollutants from these devices. More research is needed to further expand the variety of IOEDs and the richness of the test data in the future.

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