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A Review of Some Representative Techniques for Controlling the Indoor Volatile Organic Compounds

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ABSTRACT

Poor indoor air quality is now worldwide concern due to its adverse impacts on our health and environment. Moreover, these impacts carry a significant burden to the economy. Various technical approaches (e.g., biological, activated carbon fiber (ACF), photocatlytic oxidation (PCO), etc.) have gained popularity in controlling indoor volatile organic compounds (VOCs). This is because removing indoor VOC sources or increasing ventilation rates is often not feasible or economical. This review provides an overview of the various air purification technologies used widely to improve indoor air quality. Although most of these technologies are very useful to remove indoor VOCs, there is no single fully satisfactory method due to their diversity and presence at the low concentration. To achieve technical innovations and the development of specific testing protocols, one should possess a better knowledge on the mechanisms of substrate uptake at VOC concentrations.

Key words: Volatile organic compounds (VOCs), Indoor air quality, Biological treatment, Activated carbon fiber (ACF), Photocatlytic oxidation (PCO)

1. INTRODUCTION

Indoor air quality (IAQ) remains a very important issue today because it can affect human life in many respects (such as health, comfort, satisfaction, and productivity). In the present world, majority of people spend most of their time in indoor environments, e.g., residences, public buildings, and offices (US EPA, 2002; Klepeis *et al.*, 2001; Robinson and Nelson, 1995). With the improvement of living standard and innovation of construction technology, modern airtight buildings are equipped with air-conditioning systems and synthetic materials for decorating and remodeling purposes. The concentration level of indoor air pollutants can increase several hundred times higher than that of outdoor ones (Orwell *et al.*, 2004; Fisk, 2000; Brown, 1997). The prevalence of volatile organic compounds (VOCs) (e.g., formaldehyde, benzene, toluene, xylene, etc.) in indoor environment may trigger immediate or persistent harm to human health (Wolkoff, 2003). The phenomena of sick building syndrome (SBS), building related illness (BRI), or multiple chemical sensitivity (MCS) have been reported frequently in recent years (Liu, 2007; Runeson *et al.*, 2006).

There are a variety of approaches for controlling VOCs in indoor environments such as source control, ventilation, and air cleaning (Lu *et al.*, 2010). Ventilation is commonly the most efficient method but can be disadvantageous for requiring more energy consumption (Khoukhi *et al.*, 2007). At present, air purification remains to be one of the most promising air-cleaning methods to involve diverse control techniques, e.g., adsorption by activated carbon, photocatalytic oxidation (PCO), biological treatment (biofiltration, bioscrubber, vegetation approach, etc.), catalytic oxidation, adsorption, ionization methods (plasma, photocataytic oxidation, etc.), and other miscellanea ous ones (Ao and Lee, 2003; Shen and Ku, 2002). This paper presents a critical review on the potential and limitation of the three air purification technologies (i.e., biological treatment, ACF, and PCO) in light of the widest applicabiluity indoor air quality management.

2. VOCS AND INDOOR AIR QUALITY

Hundreds of VOCs with diverse physical, chemical, and biological properties can be found simultaneously in indoor air. Indoor VOC concentrations are generally higher than outdoor concentrations because VOCs can be released from human activities and a wide variety of indoor sources such as floorings, linoleum, carpets, paints, surface coatings, furniture, etc (Yu and Crump, 1998). These compounds exhibit very large variations in concentration as the composition of the mixture

released from many sources gradually varies through time. However, there are also certain substances of which release depends on punctual human activities or even human breathing (Miekisch *et al.*, 2004; Phillips, 1997; Ekberg, 1994). Indoor VOC concentrations can be controlled further by such variables as the total space volume, the pollutant production and removal rates, air exchange rate with the outside atmosphere, and the outdoor VOC concentrations (Salthammer, 1997).

Furniture coatings were found to release as many as 150 diffent VOCs (mainly aliphatic and aromatic aldehydes, aromatic hydrocarbons, ketones, etc.) (Salthammer, 1997). As several hundreds contaminants can be found simultaneously, they can result in significant rise in total volatile organic compound (TVOC) levels (Yu and Crump, 1998; Kostiainen, 1995). The effect of such rise on human health hazard is not easy to evaluate, as this generic parameter does not reflect the individual differences in toxicities between indoor air VOCs. However, symptoms (such as headache, drowsiness, fatigue, and confusion) have been recorded in subjects exposed to 22 VOCs (Hudnell *et al.*, 1992). In addition, many harmless VOCs can react with oxidants such as ozone, producing highly reactive compounds that can be more harmful than their precursors (Sundell, 2004; Wolkoff and Nielsen, 2001; Wolkoff *et al.*, 1997). Commonly available VOCs in indoor environment and their sources are listed in Table 1.

3. INDOOR AIR TREATMENT

3.1 Biological Treatment

Most of the biological treatments for indoor pollutants primarily focused on botanical purifiers. In some previous studies, it was found that ornamental indoor plants have the ability to remove harmful VOCs from indoor air (Claudio, 2011; Yang *et al.*, 2009; Tarran *et al.*, 2007; Orwell *et al.*, 2006; Wood *et al.*, 2003). Previous studies revealed that indoor plants could reduce stress and boost performance levels at work because they could soak up harmful air pollutants which may otherwise cause drowsiness, fatigue, and heavy-head feeling (Burchett *et al.*, 2008; Fjeld, 2002). In Table 2 a list of plants suitable for removing individual pollutants is listed with their potential for individual VOC.

In a pioneer study supported by the NASA, Wolverton and coauthors (1984) demonstrated the potential of plants (and their rizosphere) to remove indoor VOCs in sealed chamber. In their earliest study, these authors found that several plants could remove formaldehyde at 15,500-37,500 ppb, benzene and trichloroethylene

Table 1. Commonly available VOCs in indoor environment and their sources (Tucker, 2001).

Order	Chemical	Source
1	Acetone	Paint, coatings, finishers, paint remover, thinner, caulking
2	Aliphatic hydrocarbons (octane, decane, undecane hexane, isodecane, mixtures, etc.)	Paint, adhesive, gasoline, combustion sources, liquid process photocopier, carpet, linoleum, caulking compound
3	Aromatic hydrocarbons (toluene, xylenes, ethylbenzene, benzene)	Combustion sources, paint, adhesive, gasoline, linoleum, wall coating
4	Chlorinated solvents (dichloromethane or methylene chloride, trichloroethane)	Upholstery and carpet cleaner or protector, paint, paint remover, lacquers, solvents, correction fluid, dry-cleaned clothes
5	n-Butyl acetate	Acoustic ceiling tile, linoleum, caulking compound
6	Dichlorobenzene	Carpet, moth crystals, air fresheners
7	4-Phenylcyclohexene (4-PC)	Carpet, paint
8	Terpenes (limonene, a-pinene)	Deodorizers, cleaning agents, polishes, fabrics, fabric softener, cigarettes

Table 2. VOC removal efficiency by indoor plants over 6 h duration (Yang *et al*., 2009).

Order	Plant	VOC removal efficiency ($\mu g\ m^{-3}\ m^{-2}\ h^{-1}$)					
		Benzene	Toluene	Octane	Trichloroethylene (TCE)	α-Pinene	Total
1	Hemigraphis alternata	5.54±0.29	9.63±0.94	5.58±0.68	11.1±0.99	12.2±1.61	44.0±2.98
2	Hedera helix	3.63±0.33	8.25±0.64	5.10±0.49	8.07±0.77	13.3±0.95	38.3±3.17
3	Tradescantia pallida	3.86±0.58	9.10±1.12	2.76±1.08	7.95±1.20	10.5±1.78	34.1±5.52
4	Asparagus densiflorus	2.65±0.24	7.44±0.28	3.76±0.64	6.69±0.49	11.4±0.78	31.9±2.40
5	Hoya carnosa	2.21±0.21	5.81±0.67	3.80±0.62	5.79±0.75	8.48±1.17	26.1±3.40
6	Ficus benjamina	1.66±0.07	5.06±0.19	3.98±0.19	4.74±0.15	4.68±0.40	24.1±0.86
7	Polyscias fruticosa	1.53±0.08	4.29±0.04	3.43±0.08	3.98±0.16	8.30±0.12	21.5±0.42
8	Frttotia argroneuro	2.74±0.28	5.09±0.23	1.77±0.25	6.15±0.36	4.30±0.39	20.1±1.46

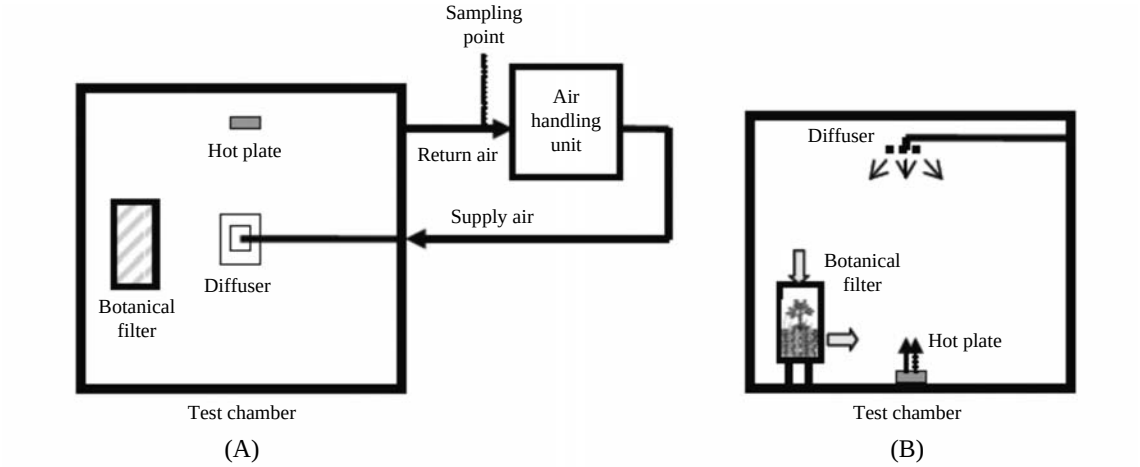

Fig. 1. Schematic diagram of the chamber test setup by indoor plants: (A) top-view and (B) side-view.

at 102-686 ppb in 24 h (Wolverton *et al.*, 1989; Wolverton *et al.*, 1984). Through their research, Wolverton and Wolverton (1993) also found that the air-cleaning capacity of houseplants can be improved exponentially by increasing air circulation to the roots of the plants, where symbiotic microorganisms can help make the bioavailable substances culled. Orwell *et al.* (2004) investigated the potential of indoor plants for removing benzene in sealed chamber (0.216 m^3) and found that microorganisms of the plant rizosphere were mainly responsible for its removal (12-25 ppm d^{-1}). These results were obtained at high initial benzene concentrations (25-51 ppm). They observed that benzene removal rate increased linearly with the dosed concentration, suggesting that the system should be inefficient under typical indoor air conditions. The same team in another experiment demonstrated that plants significantly reduced toluene and xylene at indoor air concentrations of 203-235 ppb (Orwell *et al.*, 2006). Tarran *et al.* (2007) found that indoor-plants could reliably reduce TVOC by 75% in their laboratory studies (with nine species) and field studies (in 60 offices). In a previous study, it was observed that three plants in a real office of average area 13 m^2 (volume 32.5 m^3) were more than enough to reduce TVOC by up to over 75% with or without air-conditioning (Wood *et al.*, 2006). Nevertheless, studies have demonstrated that it was the microorganisms at the root-zone of the plants which were the primary removal agents of the VOCs (Orwell *et al.*, 2006). Therefore, if the polluted air is introduced into a plant root system and degraded by the microorganisms, the removal capacity of the plant can be improved further than the potted plant with leaf effect only. Studies also showed that plants grown in hydroculture were more effective in removing VOCs than soil-grown plants, primarily due to increased air flow to root microbes (Burchett, 2005). Hydroculture also has many other added benefits such as reducing the incidence of mold and mildew as the surface remains dry (Burchett, 2005).

Many parameters such as the interfacial areas, the moisture content, and the hydrophobicity of the selected biomass can influence pollutant removal in biological purifiers. Sandhu (2007) suggested that bacteria growing on plant leaves could also contribute to VOC biodegradation. Direct pollutant accumulation or degradation by plants has however been demonstrated to occur during phytoremediation of contaminated soils (Newman and Reynolds, 2004). The ability of plant leaves to directly take up and remove pollutants for air treatment is still however open for debate (Schäffner *et al.*, 2002; Schmitz *et al.*, 2000; Wolverton *et al.*, 1984).

Just placing a few plants inside a building will not solve a serious IAQ problem, while ventilation alone cannot take such role either (Girman *et al.*, 2009). Several factors should be considered concurrently to optimize the use of plants for the improvement of indoor quality. Note that the output of chamber studies can be meaningful, if concentrations selected for such tests can actually represent those present in actual indoor environments. Moreover, chamber study results should be reported as mass of pollutant removed per hour per plant mass to facilitate direct comparisons with other removal methods. The schematic of a sample chamber test set-up is shown in Fig. 1.

3. 2 Activated Carbon Fiber (ACF)

Adsorption process is one of the most efficient and safest processes to remove VOCs from indoor air (Bastani *et al.*, 2010; Benne and Griffith, 2009). Activated carbon fiber (ACF) filter is a promising technology for removing VOCs from indoor air because of its regen-

erative properties (Huang *et al.*, 2010; Yao *et al.*, 2009a; Haghighat *et al.*, 2008; Das *et al.*, 2004). ACF is generally made from rayon, polyacrylonitrile (PAN), or phenolic resin (Huang *et al.*, 2010). The fibers are woven into a fabric and then activated in steam or CO_2 at high temperatures (e.g., 800˚C). The narrow pore size contributes to the large adsorption capacity of ACF. ACF also has large surface areas, which range from 1000 to 2400 m^2g^{-1}, with a typical value of 1800 m^2g^{-1} (Huang *et al.*, 2010; Lorimier *et al.*, 2005; Das *et al.*, 2004). ACF does not contain impurities that can catalyze oxidative reactions and lead to decomposition of the adsorbate within the adsorbent (Das *et al.*, 2004). Accordingly to the previous studies, ACF filters are very good VOC adsorbents, to show improved performance relative to granular activated carbon, zeolites, and silica gel under identical operation conditions (Huang *et al.*, 2010; Das *et al.*, 2004; Liu, 1992).

To utilize the ACF filter more efficiently, it can require regeneration step in which the adsorbed VOCs must be periodically desorbed from the filter (and exhausted outdoors). There are three different regeneration methods for the filters ((i) using outdoor air under ambient conditions, (ii) with humidified air, and (iii) with heated air). Among these options, the best performance was achieved by regenerating it for 15 minutes once every 12 hours by employing heated air up to 150˚C (Dombrowski *et al.*, 2004). The air flow during regeneration was maintained as only 1 percent of the total airflow during the 12-hour period of air cleaning (Dombrowski *et al.*, 2004). Hence, only a very small amount of air needs to be heated, regarding the small amount of energy for regeneration.

Although activated carbon filters can remove a broad range of VOCs from indoor air, their capacity to adsorb formaldehyde is relatively low (Fisk, 2007). Huang *et al.* (2010) studied the performance of ACF with a mixture of VOC (a molecular weight of 30 to 156 and boiling point of −21 to 196˚C). The time-averaged removal efficiency of all except formaldehyde was above 70 percent, while that of formaldehyde was approximately 20 percent. However, using a double layer, ACF cloth, Huang *et al.* (2010) found such efficiency can be raised to 40 percent, while those of others also exceeded 90 percent.

ACF media has a long adsorption life time and can

Table 3. Percent removal efficiency and air cleaning effectiveness ratio for ACF with different regeneration techniques (VOC source emission rate=6.4 ppb h^{-1} for each compound).

VOCs	Conditions	Percent removal efficiency	VOC cleaning ratio (*Ri*)	Reference
Benzene		60	0.26	Sidheswaran *et al.*, 2012
1-Butanol	Heated outdoor	71	0.23	Yao *et al.*, 2009b
Toluene	air regeneration	65	0.24	Lorimier *et al.*, 2005
o-Xylene	and outdoor air	73	0.22	Yao *et al.*, 2009b
Limonene	ventilation rate	73	0.22	Sidheswaran *et al.*, 2012
Undecane	of 0.4 h^{-1}	76	0.21	Sidheswaran *et al.*, 2012
Formaldehyde		24	0.56	Yao *et al.*, 2009b
Benzene		46	0.33	Sidheswaran *et al.*, 2012
1-Butanol	Unheated outdoor	53	0.29	Yao *et al.*, 2009b
Toluene	air regeneration	60	0.26	Lorimier *et al.*, 2005
o-Xylene	and outdoor air	56	0.28	Yao *et al.*, 2009b
Limonene	ventilation rate	54	0.29	Sidheswaran *et al.*, 2012
Undecane	of 0.4 h^{-1}	54	0.29	Sidheswaran *et al.*, 2012
Formaldehyde		16	0.72	Yao *et al.*, 2009b
Benzene		60	0.36	Sidheswaran *et al.*, 2012
1-Butanol	Heated outdoor	71	0.31	Yao *et al.*, 2009b
Toluene	air regeneration	65	0.33	Lorimier *et al.*, 2005
o-Xylene	and outdoor air	73	0.30	Yao *et al.*, 2009b
Limonene	ventilation rate	73	0.30	Sidheswaran *et al.*, 2012
Undecane	of 0.6 h^{-1}	76	0.29	Sidheswaran *et al.*, 2012
Formaldehyde		24	0.71	Yao *et al.*, 2009b
Benzene		46	0.44	Sidheswaran *et al.*, 2012
1-Butanol	Unheated outdoor	53	0.40	Yao *et al.*, 2009b
Toluene	air regeneration	60	0.36	Lorimier *et al.*, 2005
o-Xylene	and outdoor air	56	0.38	Yao *et al.*, 2009b
Limonene	ventilation rate	54	0.39	Sidheswaran *et al.*, 2012
Undecane	of 0.6 h^{-1}	54	0.39	Sidheswaran *et al.*, 2012
Formaldehyde		16	0.88	Yao *et al.*, 2009b

be used effectively to remove indoor VOCs with periodic regeneration (Ramirez *et al.*, 2005). The isotherm data obtained for the ACF showed that it took about 100 hours to fully saturate the ACF media with realistic concentrations of indoor VOCs (Sidheswaran *et al.*, 2011). Yao *et al.* (2009b) suggested that short periods of DC electrical heating (150 to 200˚C) of the carbon fibers was a promising option for periodically regenerating ACF. As an alternative to DC heating of the ACF media, regeneration might be accomplished by passing heated air through the ACF media (Sidheswaran *et al.*, 2011). During the heating period, air is supplied through the ACF at a low flow rate to be exhausted outdoors. This process can also re-transport the desorbed VOCs vented from the building. As an alternative to DC heating (of the ACF media), regeneration can be accomplished by passing heated air through the ACF media (Ramirez *et al.*, 2005). Moreover, results from periodic adsorption and desorption experiments showed that the ACF media should be easily regenerated after a 12 or 24 hour period of air cleaning (Sidheswaran *et al.*, 2011).

Modeling indicates that the combination of ACF air cleaning and a 50 percent reduction in ventilation can decrease indoor concentrations of VOCs by 60 to 80 percent, while reducing formaldehyde by 12 to 40 percent (Yao *et al.*, 2009b). Thus, the system can suppress exposures to VOCs and formaldehyde, while simultaneously reducing the ventilation (up to half) to save energy. However, it is essential to optimize parameters such as duration and frequency of regeneration cycles, the air flow rate, and temperature. The ACF system must be energy efficient compared to the traditional ventilation process, while still capable of providing sufficient regeneration during periods of building occupancy (Sidheswaran *et al.*, 2011). Nevertheless, most previous studies of ACF to remove indoor VOCs were limited to high concentrations of VOCs (ppm) with a few limited target compounds (Benne and Griffith, 2009). However, to allow a reduction in ventilation rates, an air cleaning system needs to be effective in removing a broad spectrum of VOCs that are present simultaneously in the indoor air at low ppb-level concentrations. Table 3 shows the percent removal efficiency of different VOCs and the corresponding air cleaning ration (*Ri*) values for different conditions. Here, *i* is defined as the ratio of the indoor VOC concentration with an air handling unit with the ACF filter installed in the system to the indoor VOC concentration with an air handling unit without the ACF filter. It was observed that in both the low ($0.4\,h^{-1}$) and high ($0.6\,h^{-1}$) ventilation rates, the system equipped with heated ACF filter bed performed better than the system without it. It was also observed that cases in which ACF was regenerated by heating have lower *Ri* values than the corresponding cases in which ACF was regenerated with unheated outdoor air. This suggests that the heated regeneration method should improve ACF VOC-removal performance compared to the unheated outdoor air regeneration method. The schematic diagram of the experimental set-up used for the regeneration of ACF is shown in Fig. 2. The regeneration of ACF was carried out by electrical heating and nitrogen flow. A complete regeneration of ACF typically requires temperature of ~150˚C and regeneration time of 60-75 min. The temperature is monitored by a thermocouple fixed at the surface of the ACF sample. The concentration of the exit gas from the reactor can be measured with the help of a gas chromatography (GC) using flame ionization detector (FID).

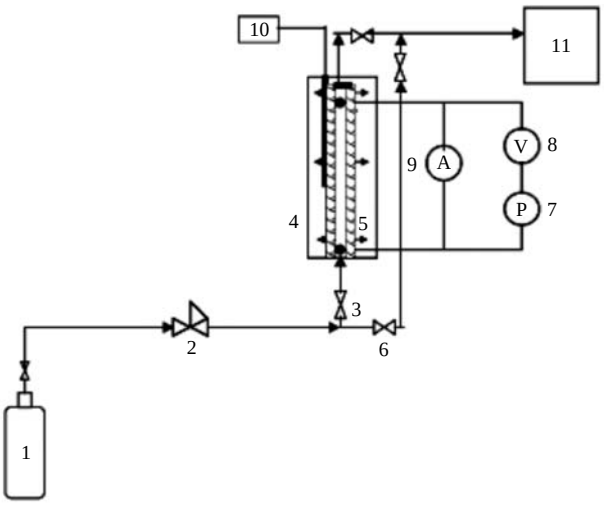

Fig. 2. Schematic diagram of the experimental set-up for the regeneration of ACF (1. N_2 gas cylinder, 2. Mass flow controller, 3. Isolation valve, 4. SS shell, 5. ACF wrapped over Teflon tube, 6. Isolation bypass valve, 7. DC generator, 8. Voltmeter, 9. Ammeter, 10. Thermocouple with PID controller, 11. GC with FID).

3.3 Photocatalytic Oxidation (PCO)

Photocatlytic oxidation (PCO) is a promising technology for the remediation of organic pollutants which has been under development for a number of years (Tompkins *et al.*, 2005; Zhao and Yang, 2003). It is a cost-effective technology for VOCs removal compared with adsorption, biofiltration, or thermal catalysis (Dvoranova *et al.*, 2002; Kim *et al.*, 2002). PCO process harnesses radiant energy from natural (or artificial) light sources with heterogeneous catalyst to degrade the organic pollutants into their mineral components (Li *et al.*, 2005a; Ao *et al.*, 2004; Hoffmann, 1995). Titanium dioxide (TiO_2) is the most widely used

catalyst for the photocatalytic reaction (Wang *et al.*, 2007). Other semiconductors (such as ZnO, ZnS, CdS, Fe_2O_3, and SnO_2) are also commonly used catalysts (Wang *et al.*, 2007). The PCO process creates hydroxyl radicals and super-oxide ions, which are highly reactive electrons (Pichat *et al.*, 2000). These highly reactive electrons aggressively combine with the air pollutants (e.g., VOCs). Once bound together, the chemical reaction takes place between the super-charged ion and the pollutant to effectively oxidize (or burn) the pollutant. This breaks the pollutants down into harmless components (carbon dioxide and water molecules), making the air more purified (Hodgson *et al.*, 2007).

Wang *et al.* (2007) supplied VOCs contaminated air over a titanium dioxide (TiO_2) catalyst at room temperature, while illuminating with a black lamp. These authors found that over 95% of the VOCs were converted to carbon dioxide and water. At 70˚C, the reaction rates were three to four times faster than at room temperature. They also revealed that a platinum-doped (Pt/TiO_2) catalyst could achieve even higher reaction rates without producing any detectable carbon monoxide (Wang *et al.*, 2007). Performance of the Pt/TiO_2 catalyst was improved further with increasing temperature with both thermal and photocatalytic effects to contribute to the compound destruction (Wang *et al.*, 2007). The best performance was obtained at 150˚C which was the highest temperature selected for their testing (Wang *et al.*, 2007). Addition of ozone to the air stream also increased the process efficiency, but the use of ozone can raise safety and cost issues. Stevens *et al.* (1998) reported the operational characteristics of four PCO reactor designs using P25 TiO_2 for the oxidative destruction of formaldehyde, acetaldehyde, and acetone. Their result showed that photodegradation of acetaldehyde was lower than that for formaldehyde and acetone. PCO of the formaldehyde and acetone was nearly 100% for all reactor designs (Stevens *et al.*, 1998). Cao *et al.* (2000) investigated the nanoscale TiO_2 catalysts for the photocatalytic oxidation of toluene. They found that the nanoscale TiO_2 samples were highly active for the photodegradation of toluene. However, the use of platinum loaded on TiO_2 could facilitate the removal of poisonous intermediates from the deactivated TiO_2 surface, while resulting in lower oxidation rates of toluene (Cao *et al.*, 2000). Pichat *et al*. (2000) employed a TiO_2 coated fiber glass mesh composed of anatase TiO_2 and SiO_2 for photocatalytic oxidation of benzene, toluene, and xylenes (BTX) in indoor air. According to their study the average concentrations of BTX were indeed reduced by a factor of 2-3 in an ordinary non-airtight room.

Li *et al.* (2005b) reported that the photocatalytic efficiency of the TiO_2 catalysts with the lanthanide ion doping can exhibit remarkably enhanced removal efficiency for BTEX. The 1.2% Ln^{3+}-TiO_2 catalysts achieved the highest photocatalytic activity. The enhanced photo degradation of BTEX is possibly due to the improved adsorption ability and the enhanced electron-hole pairs separation due to the presence of Ti^{3+} on the surface of Ln^{3+}-TiO_2 catalysts and the electron transfer between the conduction band/defect level and lanthanide crystal field state (Li *et al.*, 2005b). Shiraishi *et al.* (2005) developed a high-performance photocatalytic reactor with a parallel array of nine light sources for photocatalytic decomposition. These authors found that this photocatalytic reactor can rapidly decompose HCHO toward zero concentration. It was recognized that at high humidity levels, water vapor competed with TiO_2 for adsorption sites which decreased the rate of PCO.

To improve this situation, Ao and Lee (2003) developed an activated carbon (AC) filter immobilised with TiO_2 (TiO_2/AC). The results indicated that the removal efficiency of TiO_2/AC was seven times higher than TiO_2 under high humidity levels. Shen and Ku (2002) found that the addition of ozone into the TiO_2/UV/TCE system with 254 or 365 nm UV lamps reduced the removal of TCE, possibly because excessive ozone molecules could scavenge hydroxylradicals produced from the excitation of TiO_2 by UV radiation. Kirchnerova *et al.* (2005) explored the photocatalytic activities of two commercial TiO_2 catalysts, Degussa P25 and Hombicat UV100, for n-butanol decomposition under visible light. They found that Degussa P25 was more active than Hombicat UV100. One new approach to produce visible-light activated TiO_2 photocatalysts is by doping with anions such as N^{3-}, C^{4-}, S^{4-} or halides (F^-, Cl^-, Br^-, and I^-) (Belver *et al.*, 2006). It was suggested that these species substitute the oxygen lattice on TiO_2 and lead to a band gap narrowing which may ultimately lead to high visible absorption.

Yu *et al.* (2009) found that only the surface area of the reactor influenced the PCO rate sensitively, while the UV light had a better PCO effect than that of visible light. Hence, the consumption condition of the UV light in indoor will be an important issue of further studies. Yu and Brouwers (2009) conducted photocatalytic oxidation experiments at room temperature under visible light and demonstrated its convenience for the indoor air purification. Besides the photocatalyst, no other materials are required for the degradation of indoor air pollutants. However, hexamethyldisilazane cannot be treated effectively using PCO techniques. Because of silicon containing reaction products, the catalyst is deactivated minutes after hexamethyldisilazan contact (Wang *et al.*, 2007). The catalyst can hence

Table 4. Comparison of catalyst system used for VOCs degradation under UV-light.

Catalyst	VOCs	λ (nm)	Initial concentration (ppb)	Conversion (%)	Reference
TiO_2 (5%)	Formaldehyde	356	15	80	Stevens *et al.*, 1998
TiO_2 (5%)	Acetaldehyde	356	15	60	Stevens *et al.*, 1998
TiO_2 (5%)	Acetone	356	15	100	Stevens *et al.*, 1998
TiO_2 (6.8%)	Benzene	365	15	30	Pichat *et al.*, 2000
TiO_2 (6.8%)	m-Xylene	365	40	50	Pichat *et al.*, 2000
TiO_2 (6.8%)	p-Xylene	365	60	55	Pichat *et al.*, 2000
TiO_2 (6.8%)	o-Xylene	365	20	50	Pichat *et al.*, 2000
TiO_2 (20%)	Benzene	352	93	100	Jo *et al.*, 2000
TiO_2 (20%)	m-Xylene	352	78	100	Jo *et al.*, 2000
TiO_2 (20%)	p-Xylene	352	78	100	Jo *et al.*, 2000
TiO_2 (20%)	o-Xylene	352	45	100	Jo *et al.*, 2000
TiO_2 (20%)	Ethyl benzene	352	21	100	Jo *et al.*, 2000
TiO_2 (5%)	Benzene	365	20	70	Ao and Lee, 2003
TiO_2 (5%)/AC	Benzene	365	20	80	Ao and Lee, 2003
TiO_2 (5%)	Toluene	365	20	88	Ao and Lee, 2003
TiO_2 (5%)/AC	Toluene	365	20	88	Ao and Lee, 2003
TiO_2 (1%)	Benzene	355	88	5	Strini *et al.*, 2005
TiO_2 (1%)	Toluene	355	80	24	Strini *et al.*, 2005
TiO_2 (1%)	Ethyl benzene	355	65	48	Strini *et al.*, 2005
TiO_2 (1%)	o-Xylene	355	60	54	Strini *et al.*, 2005
TiO_2 (5%)	Benzene	365	23	4	Li *et al.*, 2000b
La (1.2%)/TiO_2 (5%)	Benzene	365	23	30	Li *et al.*, 2000b
Nd (1.2%)/TiO_2 (5%)	Benzene	365	23	22	Li *et al.*, 2000b

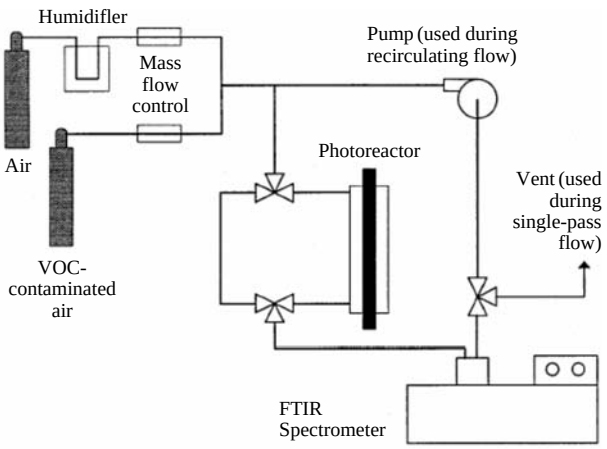

Fig. 3. Schematic diagram of the photo catalytic oxidation setup.

be reactivated partially by flushing with water or other solvents. Nonetheless, the speed with which deactivation takes place renders any sort of regeneration process impractical (Wang *et al.*, 2007).

Table 4 summarizes the results on various photocatalytic oxidations for indoor VOCs. The schematic diagram of the PCO setup for indoor air assessment is also plotted in Fig. 3. This experimental setup is composed of the reactor, gas supply, analyzer, parameters controller, etc. A known amount of photocatalyst (e.g., P25 TiO_2) is coated onto the inner wall of the glass tube. Exact photon output from the lamp is measured periodically with an ultraviolet (UV) spectrometer. The photo reactor can then be incorporated into a test system that allows researchers to vary flow rate, VOC air concentration, humidity, and temperature.

4. CONCLUSIONS

This review presents an overview of the various technical approaches (e.g., biological, ACF, and PCO) currently available for indoor air treatment. Nonetheless, there is yet no single fully satisfactory method for VOC removal from indoor air due to the difficulties linked to the very low concentration, diversity, and variability of VOCs in the indoor environment. Although the above mentioned methods have shown certain potential for the removal of VOC, the specific characteristics of indoor air pollutants and the indoor environment can yield numerous challenges. In particular, new methods must be developed to inoculate, express, and maintain a suitable and diverse catabolic ability under the conditions of trace substrate concentration. In addition, the methods for the treatment of indoor air must be able to purify a large amount of air in spatially confined environments with minimal nuisances. This requires technical innovations, the development of specific testing protocols, and a better understanding of

the activities and the mechanisms of VOC uptake by different substrates.

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