Technical Summary on VOC Removal Efficiencies of Technologies demonstrated under the Cleaner Production Partnership Programme

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4 November 2019

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1. INTRODUCTION

The Hong Kong Productivity Council (HKPC), acting as the implementation agent of Cleaner Production Partnership Programme (the Programme), has conducted a technical review on approved cleaner production (CP) technologies that are designed to reduce Volatile Organic Compound (VOC) emissions and funded under the Programme. This document is a report that summarises the findings of the technical review.

2. OBJECTIVES OF THE REVIEW

2.1 The objectives of this review are as follows:

- To understand the operations and industrial processes for the different industry sectors which adopt the VOC treatment technologies with funding support by the Programme;
- To review and compare the actual VOC removal efficiencies of various treatment technologies under a range of VOC concentrations; and
- To review the relationship between the initial investment cost to establish the treatment systems and the amount of VOC emissions expected to be treated.

DOCUMENT REVIEW OF APPROVED DEMONSTRATION PROJECTS

3.1 Since commencement of the Programme in 2008, there were in total 107 Demonstration Project (DP) applications as of the end of June 2019 that proposed adoption of end-of-pipe treatment technologies to reduce pollutants emission to the atmosphere (e.g. VOC, NOx). Of which, 54 applications adopted with end-of-pipe treatment to specifically reduce VOC emissions were reviewed (See *Note* at bottom of page 4). Factories of these 54 DPs were from seven manufacturing industries, namely, chemical products; metal and metal products; printing and publishing; furniture; textile, vehicle maintenance, and paper and paper products. See Table 1 below for a description of the industries.

Industry	**Description**
Chemical Products	The chemical products industry involves a variety of processes such as plastic melting, printing and paint spraying. Examples of plastic melting include injection moulding and pellets extrusion, which are the main sources of VOC emissions through the evaporation of organic solvents under high heat. For the paint spraying and surface coating operations, the most commonly used solvents are paint and thinner. Paint is mostly applied in spraying process toward the products surface whilst thinner is used in cleaning parts and machinery.
Metal and Metal Products	The metal and metal products industry includes both primary metal production from ore and secondary production of alloys. The main air emissions include the release of sulfur oxides, metal fumes and dust. Since most metal products require surface finishes for decorative or functional purposes, large amount of VOCs are also emitted as fugitive emissions via the coating, paint spraying, printing, curing and surface cleaning operations.
Printing and Publishing	The printing industry includes various printing processes, such as pad printing, screen printing, etc. It employs a large amount of chemicals containing VOCs, with the main source being evaporation of organic solvents contained in the inks during the drying process. Other fugitive emission sources along the printing line include the ink fountain where ink is mixed and stored, the press and the chill roll where organic solvents are used to remove inks from the roller blanket.
Furniture	Furniture manufacturing involves the use of wood, plastic, metal and other ancillary materials in the machining, assembly, coating and finishing stages. Fugitive VOC emissions related to this process usually occur in the surface finishing and drying stages, with varnishes and coating agents applied to the furniture surfaces evaporating to the atmosphere. Cleanup operations also involve the use of industrial solvents which are highly evaporative.
Textile	Textile manufacturing involves the conversion of various fabrics into clothing or textiles. The main stages include: fiber production, processing and spinning, yarn preparation, fabric production, bleaching, dyeing, and printing and finishing. VOC emissions mainly arise from the finishing and drying processes which drive off the volatile compounds in the solvents under high temperature conditions.
Vehicle Maintenance	The main source of VOC emissions in the vehicle maintenance industry is the paint spraying process on the vehicle body. Usually the spraying process takes

	place within a paint spray booth. However, if the spraying is conducted in a booth without proper control measures installed, VOCs from solvent-based paints, which are usually sprayed into the vehicle body from high pressure spray guns, would be emitted to the atmosphere via the overspray mists and vapour.
Paper/Paper Products	The paper/paper products manufacturing industry largely utilises pulp in its manufacturing process, with a variety of chemical additives added to the process at various stages such as paper pressing, coating and drying. Whilst water vapour is the primary emission due to the high-moisture content of the paper products, the additives and adhesives such as resins and solvents also contribute to significant VOC emissions in the process.

Table 1 *Description of major industrial processes involved in VOC treatment*

3.2 The key data and information collected from reports of the 54 DPs included the following:

- Operations and industrial processes for each industry (e.g. plastic moulding, paint spraying, printing);
- VOC emissions and flue gas characteristics (e.g. concentration, flow rate);
- Design of VOC treatment train system including combination of different technologies; and
- Initial investment cost for the VOC treatment technologies.

4. DATA COMPILATION AND ANALYSIS

4.1 The consolidated data was analysed and comparisons were made based on the following categorisations:

- Industry sector and industrial process
- VOC concentrations in the inlet and outlet of the treatment system
- Investment cost of the treatment system

4.2 The following performance indicators were analysed for the treatment technologies:

- VOC removal efficiency (%)

  VOC removal efficiency = difference in tonnage of VOC measured at inlet and outlet of the treatment unit / tonnage of VOC emission measured at inlet of the treatment unit

- Investment cost per waste gas (HKD per m^3/hr)
  Investment cost per waste gas = Equipment Fee / Exhaust gas flow rate measured at treatment unit inlet.

5. REVIEW OF INDUSTRY SECTORS AND PROCESSES

5.1. Industry sector breakdown

5.1.1 The industry sector breakdown for the 54 DPs is found to be very similar to the overall population (i.e. the total of 107 DPs). Three major industries involved were Chemical Products, Metal and Metal Products and Printing and Publishing. See Figure 1 below.

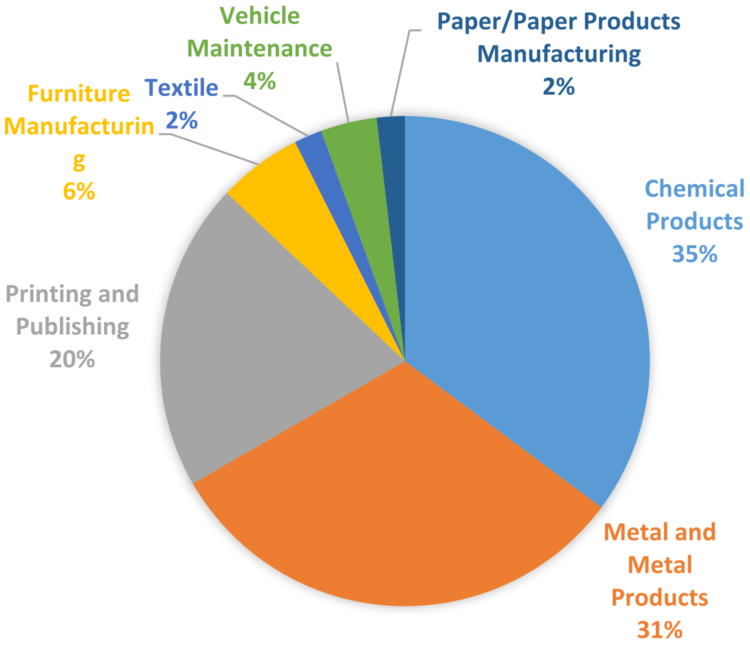

Figure 1 *Breakdown of industry sectors adopting VOC treatment technologies (54 DPs)*

5.1.2 In terms of the industrial processes by which VOCs were emitted, the top three processes were paint spraying, printing and plastic melting. The remaining processes included curing process of paints and use of solvents. Given that there were different processes employed within each industry sector, a breakdown by such process was compared and analysed (Figure 2 and Figure 3).

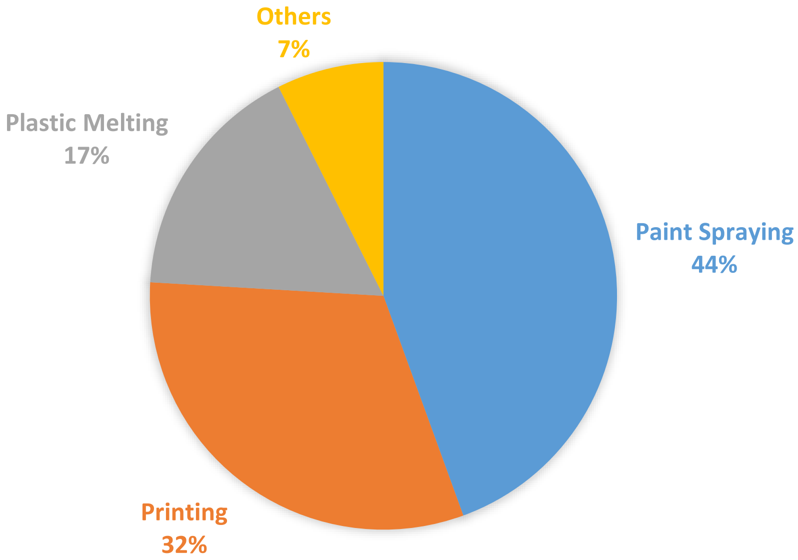

Figure 2 *Breakdown of industrial processes by which VOCs are emitted (54 DPs)*

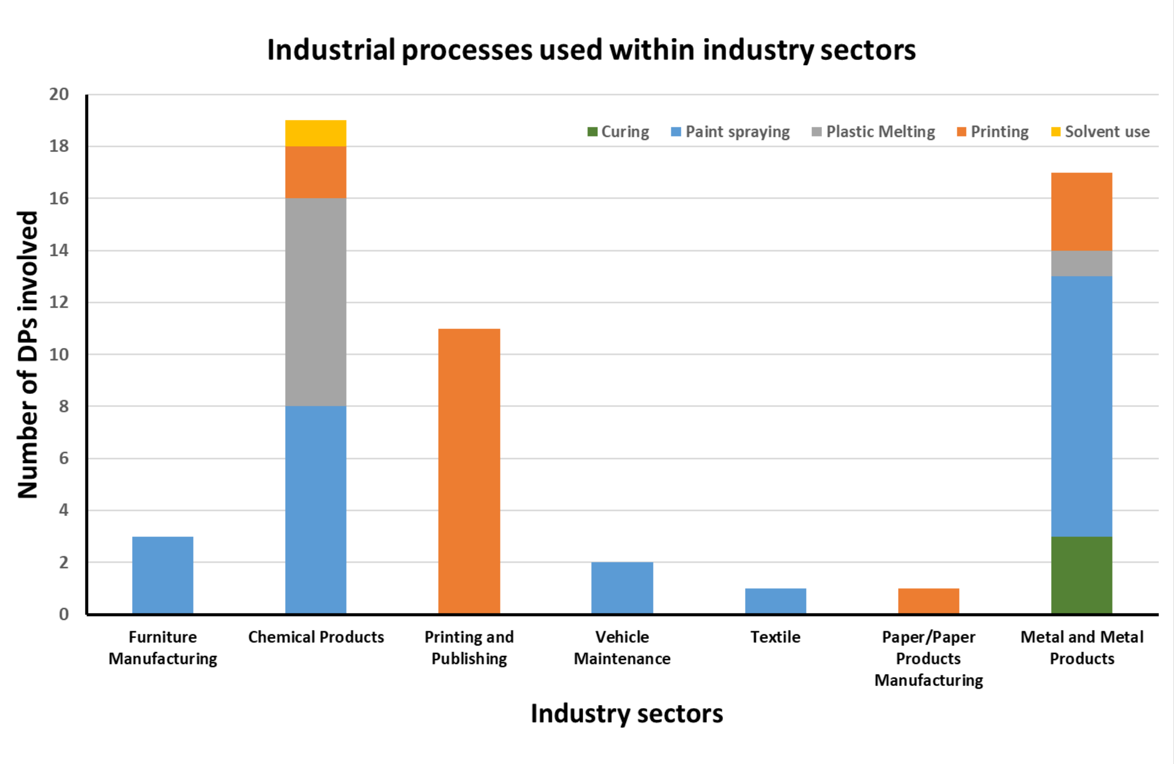

Figure 3 *Nature of industrial processes associated with each industry type (54 DPs)*

5.1.3 It can be observed from the two figures above that paint spraying and printing are the most prominent processes amongst the DPs and have been adopted across more than half of the seven industry sectors.

5.2. Inlet VOC concentrations for industrial processes

5.2.1 One of the critical factors affecting the removal efficiency of end-of-pipe treatment technologies is the initial VOC concentration entering the system. Figure 4 below shows a box and whisker plot summarising the inlet VOC concentration range for the 54 DPs categorised by their industrial processes.

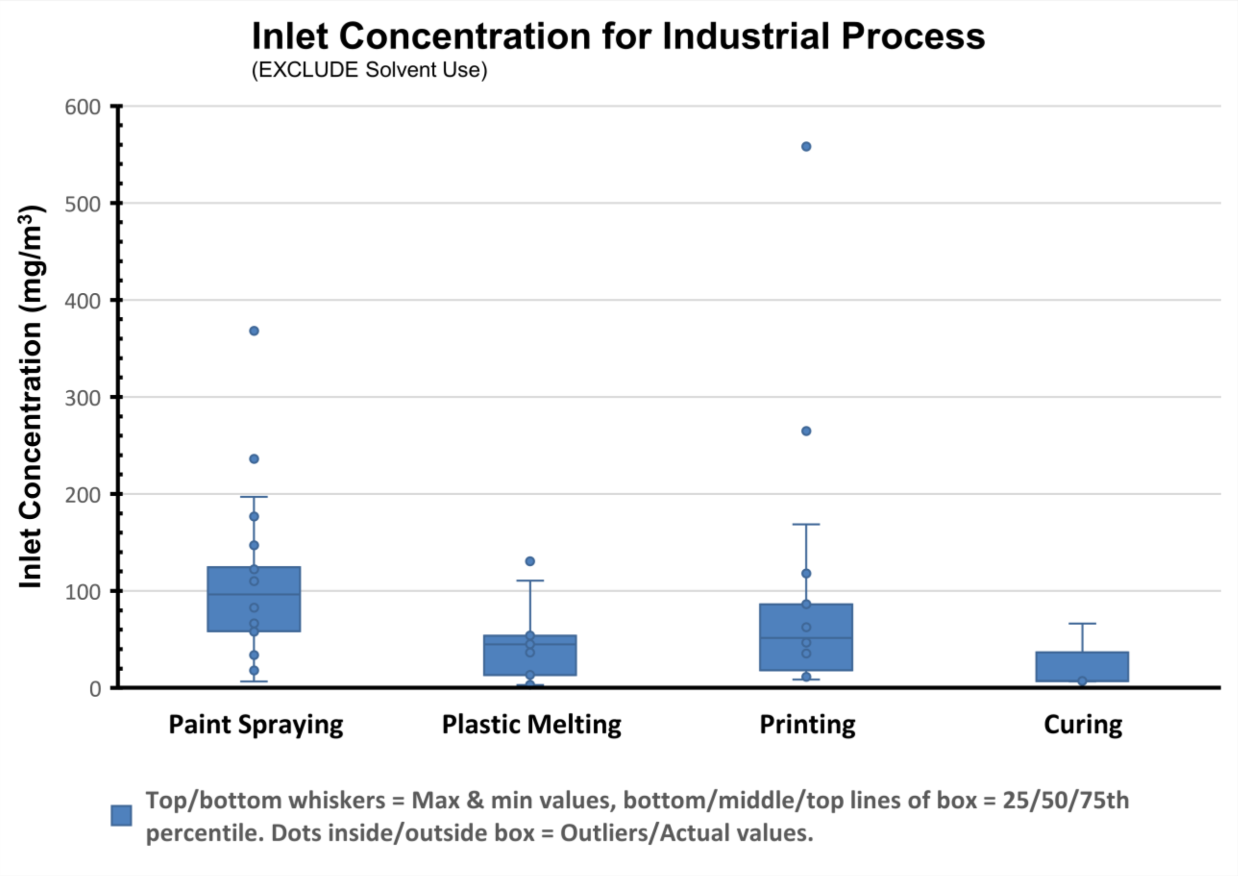

Figure 4 *VOC inlet concentrations across industrial processes*

5.2.2 Amongst the three main industrial processes (paint spraying, plastic melting, printing), paint spraying appeared to have the widest range of inlet concentrations (7 - 197 mg/m^3) and the highest median value of 96 mg/m^3, with the actual values spread out quite evenly across the quartiles. The printing process had a slightly narrower range (9 -169 mg/m^3) and a lower median value of 52 mg/m^3. Plastic melting was found to have the smallest inlet VOC range (3 -110 mg/m^3) and the lowest median of 45 mg/m^3.

5.2.3 For the other two industrial processes (curing and solvent use) discussed in section 5.1.2 , the curing process was also similar to plastic melting in terms of its low inlet VOC range. For the use of solvents, there was only one associated DP (a pharmaceuticals manufacturer), and due to its very high inlet concentration (56500 mg/m^3) it was not shown in the figure.

6. REVIEW OF VOC TREATMENT TECHNOLOGIES

6.1. Mechanisms of VOC treatment

There are different types of mechanisms for treatment of VOC emissions. The ones used in the 54 DPs are described below and also summarized in Figure 5. Note that some DPs have adopted multiple treatment method as part of their combined treatment system.

6.1.1 Ultra violet photo-catalytic oxidation (PCO): UV photo-catalytic oxidation utilises the phenomenon that when a photo-catalyst, usually titanium dioxide, is put under UV irradiation, it will undergo a photochemical reaction on its surface to release electrons which subsequently react with water molecules to form hydroxyl radicals. These highly reactive hydroxyl ions can oxidise gaseous pollutants and eventually convert them into carbon dioxide and water. Of the 54 DPs being reviewed, 17 of them have used PCO as part of the single/multiple VOC treatment systems.

6.1.2 Ultra violet degradation (UV): In UV degradation systems, the UV radiation itself in combination with the ozone generated by the UV light will effectively degrade complex organic molecules into simpler, less hazardous organic molecules such as water and carbon dioxide. The performance of the UV system depends on several factors including the UV light intensity and time exposure of the VOC molecules to UV light. Of the 54 DPs being reviewed, 8 of them have used UV as part of the single/multiple VOC treatment systems.

6.1.3 Chemical scrubbing (ChemScrub): In chemical scrubbing, a liquid is used to remove pollutants from an exhaust gas stream via absorption of the pollutants into the scrubbing liquid. Large surface area is required to create close contact between the liquid and the gas stream. A common design is a counter-current packed bed tower in which the VOC stream enters the bottom of the tower and flows upward through the media against the downward flow of the liquid. Of the 54 DPs being reviewed, 6 of them have used chemical scrubbing as part of the single/multiple VOC treatment systems.

6.1.4 Low temperature plasma (Plasma): Low temperature or non-thermal plasma is a technology based on creating a high-voltage discharge in near ambient temperature to ionize the incoming pollutant gas. The discharge generates highly reactive ions and free radicals that will degrade complex organic molecules into simpler, less hazardous molecules including water and CO_2. Of the 54 DPs being reviewed, 11 of them have used plasma as part of the single/multiple VOC treatment systems.

6.1.5 Activated carbon/zeolite adsorption (ActCarb): Activated carbon and zeolite are two examples of the use of a material with a very high internal surface area to physically attract and capture gaseous pollutants. The performance of the adsorption bed (e.g. time until bed breakthrough) will depend on a number of factors such as the depth of the adsorption bed, operating temperature, humidity as well as the type and concentration of the pollutant gases. Of the 54 DPs being reviewed, 18 of them have used activated carbon/zeolite as part of the single/multiple VOC treatment systems.

6.1.6 Thermal oxidation and catalytic thermal oxidation (Thermo/CatThermo): Thermal oxidisers are combustion devices that remove VOCs through direct thermal combustion and turn them into carbon dioxide and water. Similarly, catalytic oxidisers utilise a catalyst to promote the oxidation reaction and lower the required combustion temperature. Another modified design example is the regenerative thermal/catalytic oxidizer that cyclically pre-heats the incoming gas stream with the combustion heat previously stored in ceramic media beds. Of the 54 DPs being reviewed, 2 of them have used thermal oxidation as part of the single/multiple VOC treatment systems.

6.1.7 Cryogenic condensation (CryCon): Cryogenic condensation is a way of recovering valuable organic solvents through progressively cooling the pollutant gas to a very low temperatures which will be below the dew point of the gas stream, in order to saturate the gas stream and condense the organic molecules into liquid form. The refrigeration capacity of liquid nitrogen has enabled this technology to be used in a variety of conditions. Of the 54 DPs being reviewed, 1 of them have used cryogenic condensation as part of the single/multiple VOC treatment systems.

6.1.8 Bio-filtration (BioF): In bio-filtration, the organic contaminants in the gas stream are absorbed to an aqueous phase in a media bed where micro-organisms grow and feed on the contaminants as a carbon source, and turn them into carbon dioxide, water and organic biomass. One example is the bio-trickling filter that is designed with a continuous trickled-water flow inside the filter media for increased exposure between the VOC compounds and the microbial population. Of the 54 DPs being reviewed, 3 of them have used bio-filtration as part of the single/multiple VOC treatment systems.

6.1.9 Iron-carbon micro-electrolysis (FeC): In an iron-carbon micro-electrolysis system, the exhaust gas is put under slightly acidic condition before entering a packed tower installed with iron-carbon composite media, where micro-electrolysis reaction takes place and highly reactive hydroxide ions (OH^-) are formed to degrade macromolecular organic matters, which are then degraded to form small molecule organic matters and eventually carbon dioxide (CO_2) and water (H_2O). Of the 54 DPs being reviewed, 4 of them have used iron-carbon micro-electrolysis as part of the single/multiple VOC treatment systems.

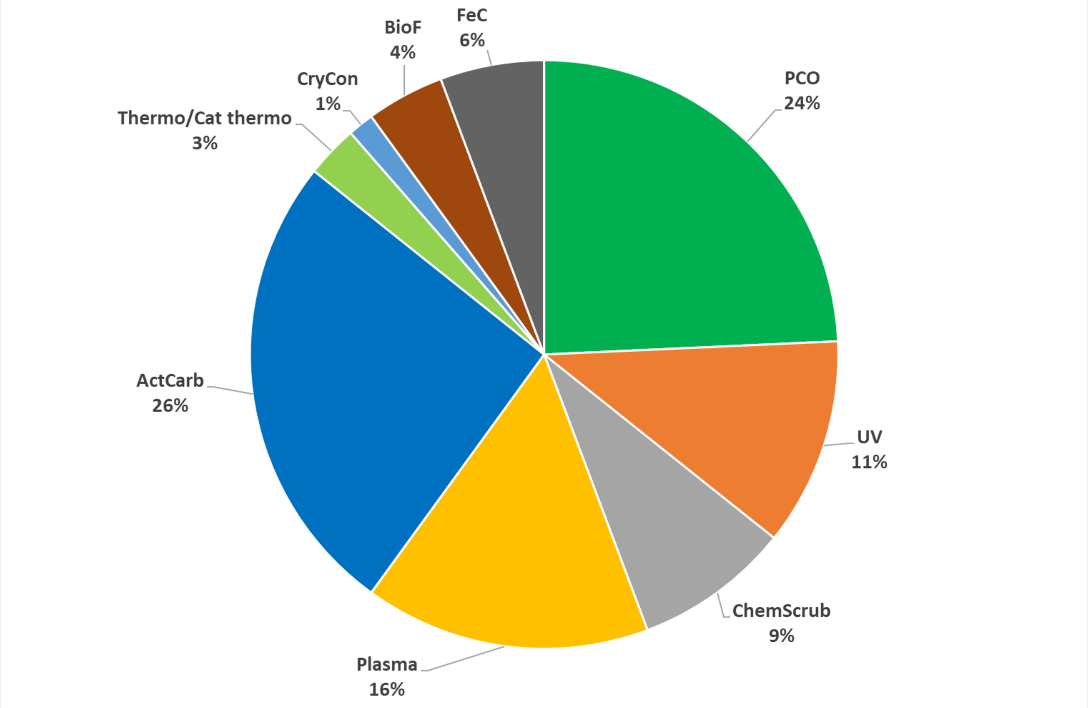

Figure 5 *Breakdown of VOC treatment technologies (54 DPs)*

6.2. Categorisation of VOC treatment technologies

6.2.1 While the VOC treatment technologies discussed in section 6.1 contain design operating features, they can be broadly divided into two categories, “collection-based” and “destruction-based”, according to the final fate of the treated pollutants. The former category includes technologies such as activated carbon adsorption, chemical scrubbing and cryogenic condensation that work to collect the organic compounds captured from the waste gas. The latter category includes techniques such as UV/photo-catalytic oxidation, thermal oxidation, plasma and bio-filtration that are designed to destroy the VOC compounds with no options for subsequent collection-based or reuse.

6.2.2 The next chapter shall discuss the actual performance of the VOC treatment techniques reported in the 54 DPs, in which most of them have adopted a multi-tier approach to treat VOCs through a combination of different technologies.

7. PERFORMANCE COMPARISON OF VOC TREATMENT TECHNOLOGIES

7.1. Overall Removal Efficiencies

7.1.1 Based on data obtained from the 54 DPs, there are up to 20 VOC treatment designs. The overall range of the VOC removal efficiency is shown in the box and whisker plot of Figure 6 below, with the combined treatment designs named after the order of the treatment train. The treatment designs have also been categorised into destruction-based or collection-based methods (see blue and green boundary lines) based on the primary treatment method used (e.g. “UV-photocatalytic + activated carbon” is considered “destruction-based”). Note that the full name of each technology has been abbreviated in section 6.1. The number of times these VOC treatment methods have been adopted in the DPs are also indicated in brackets in Figure 6 and displayed as bar chart in Figure 7.

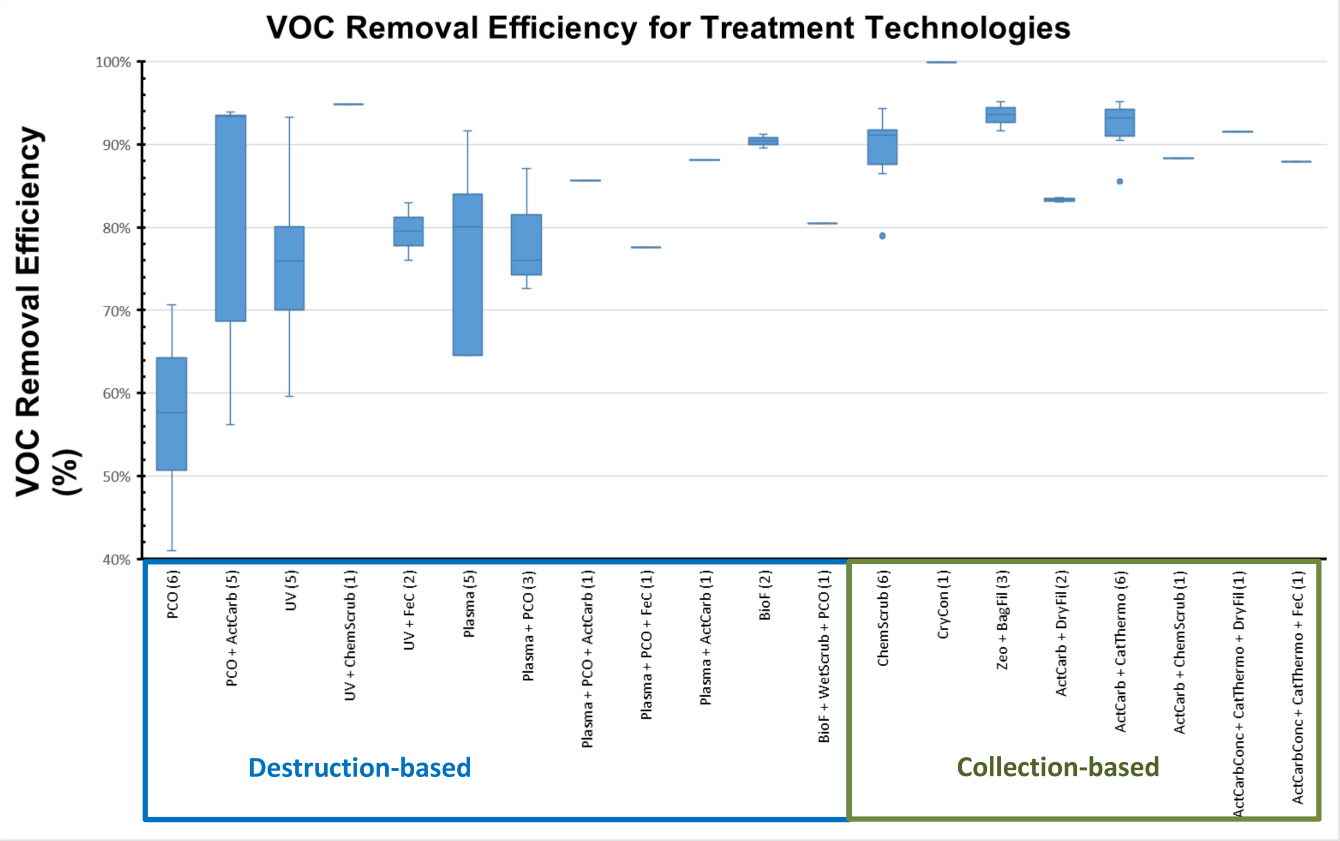

***Figure 6** Overall VOC removal efficiency of treatment techniques*

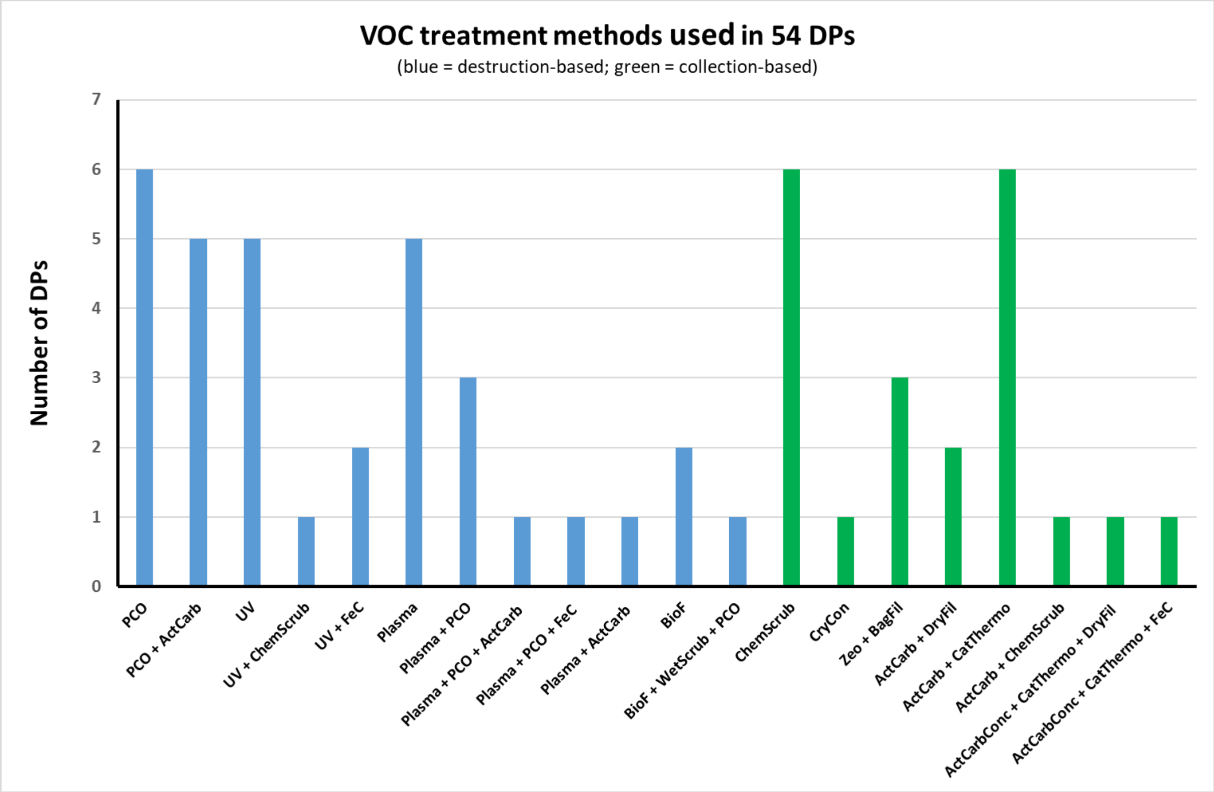

Figure 7 *VOC treatment methods used in 54 DPs*

7.1.2 A number of observations can be made based on the two graphs:

- The collection-based treatment methods, which primarily use adsorption, have achieved a VOC removal rate of above 80%. They include:
    - Chemical Scrubbing
    - Cryogenic Condensation
    - Zeolite + Bag Filter
    - Activated Carbon + Dry Filter
    - Activated Carbon + Catalytic Thermal Oxidation
    - Activated Carbon + Chemical Scrubbing
    - Activated Carbon + Catalytic Thermal Oxidation + Dry Filter
    - Activated Carbon + Catalytic Thermal Oxidation + Iron-Carbide micro-electrolysis.

- The destruction-based treatment methods, which are mainly based on UV/photo-catalytic oxidation and plasma, have achieved a lower VOC removal rate in general. They include:
    - UV Photocatalytic oxidation (PCO)
    - UV Photocatalytic oxidation + Activated Carbon
    - Ultra violet (UV) degradation
    - UV degradation + Chemical Scrubbing
    - UV degradation + Iron-Carbide micro-electrolysis (FeC)
    - Low temperature plasma

- ○ Plasma + PCO
- ○ Plasma + PCO + Activated Carbon
- ○ Plasma + PCO + FeC
- ○ Plasma + Activated Carbon
- ○ Bio-Filtration
- ○ Bio-Filtration + Wet Scrubbing + PCO

7.2. Removal Efficiencies vs Inlet Concentrations – all technologies

7.2.1 The treatment methods were analysed in terms of the inlet VOC concentrations and their corresponding removal rate, as shown in Figure 8. It was noted that there was only one DP application using cryogenic condensation, which had achieved a near 100% collection-based of solvents at a very high inlet VOC concentration of 56,500 mg/m^3. As such the figure is presented in range of inlet concentration in logarithmic scale in order to include all technologies.

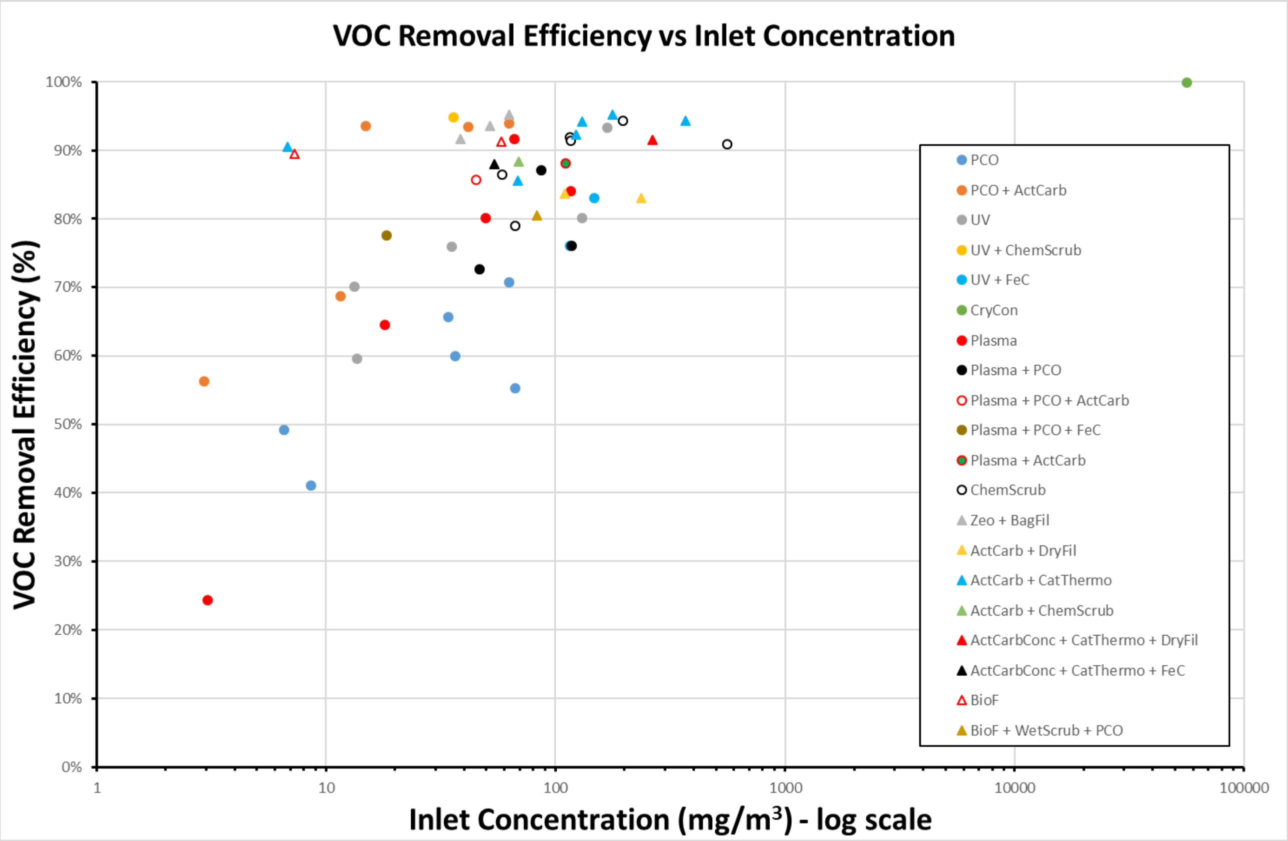

Figure 8 *VOC removal efficiency vs inlet concentration*

7.2.2 Two separate graphs excluding the DP case with cryogenic condensation are shown in Figure 9 and Figure 10, which compare the remaining technologies in a linear scale.

Figure 9 includes the inlet concentration values up to the second highest inlet concentration under 600 mg/m^3, while Figure 10 further focuses on the inlet concentrations under 200 mg/m^3, which take up 93% (or 50 out of 54) of the DPs under this study.

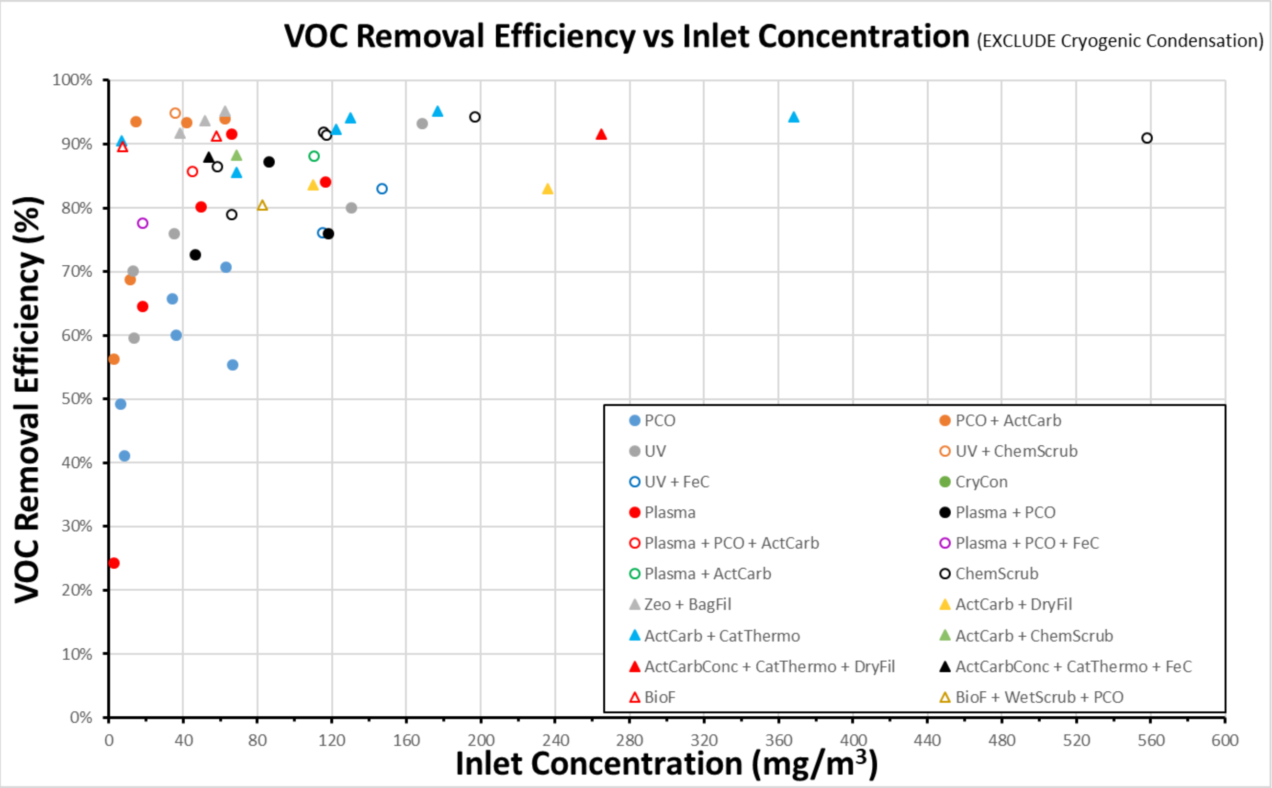

Figure 9 *VOC removal efficiency vs inlet concentration (no cryogenic cond., up to 600 mg/m^3)*

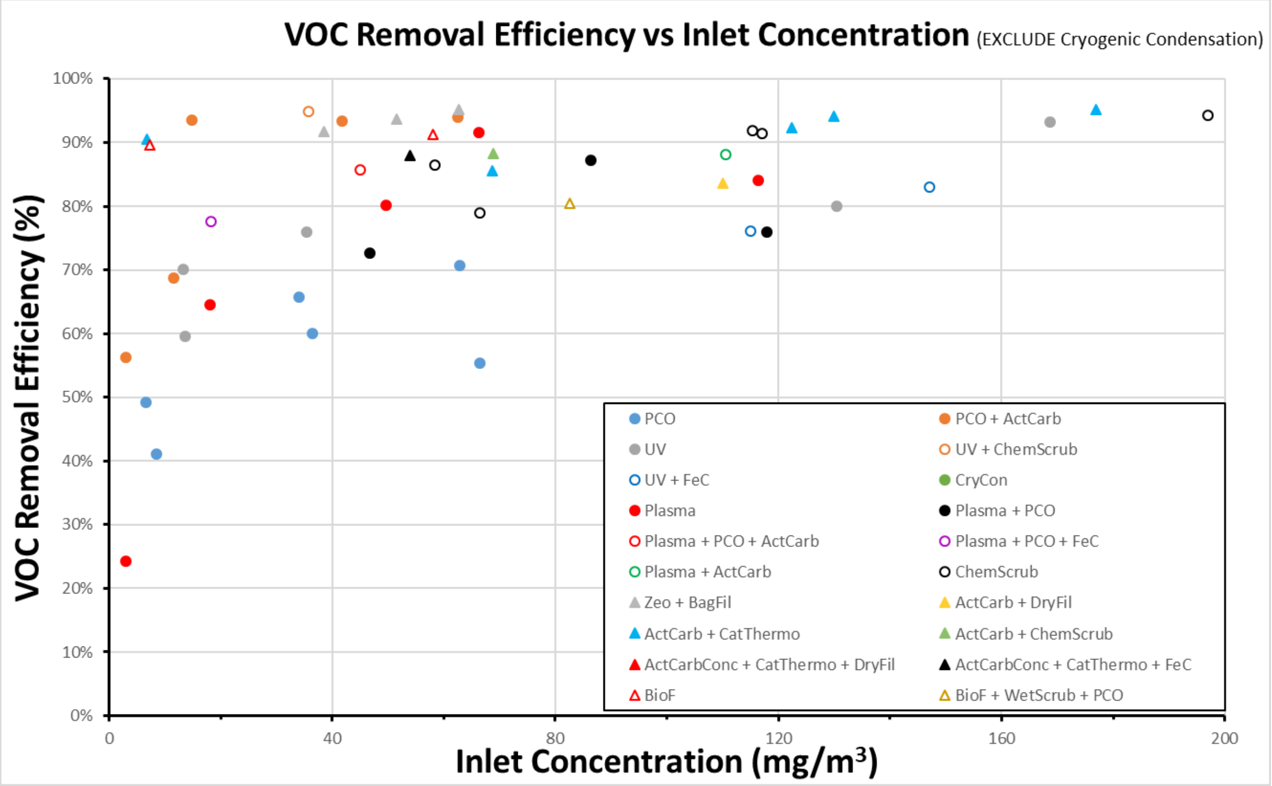

Figure 10 *VOC removal efficiency vs inlet concentration (no cryogenic cond., up to 200 mg/m^3)*

7.2.3 A number of observations can be made based on these three graphs:

- There was a general positive trend between the inlet VOC concentration and the removal efficiency, with removal efficiencies achieving above 70% for inlet concentrations over 80 mg/m^3.
- At the lower range of the inlet concentration (under 40 mg/m^3), there was a marked drop in removal efficiencies due to the condition of high flow rate with low concentrations that further dilutes the VOC concentrations.
- For the DP with the lowest removal efficiency (24%) at the lowest inlet concentration (3 mg/m^3), shown as the red dot at the bottom left of the graph, its removal efficiency was only for the additional efficiency achieved by an integrated plasma & UV-photocatalytic oxidation module that was added as a polishing unit to the end of an existing wet scrubber+ activated carbon system.

7.3. Removal Efficiencies vs Inlet Concentrations – Treatment Methods

7.3.1 The VOC removal performances are grouped according to the different nature of treatment methods discussed previously in section 6. Further analysis and comparison between the various treatment methods will be discussed in the sections to follow.

7.3.2 As discussed in section 6.2 and section 7.1, the VOC treatment methods have been broadly classified into collection and destruction-based according to the primary operating mechanism of the technology and the final fate of the VOC compounds. In this section, bio-filtration, chemical scrubbing and cryogenic condensation have been further separated from the destruction/collection classification to highlight specific details of their performance. For bio-filtration, it is a biological digestion process that is distinctly different from the rest of the destruction-based methods that utilize high-energy ionization. For chemical scrubbing, it utilizes gas-liquid absorption that is also different in nature from the physio-chemical surface adsorption used by the other collection-based treatment methods (e.g. activated carbon, zeolite). Cryogenic condensation, on the other hand, recovers VOC solvents through low temperature condensation. As such, the destruction-based category can be separated into the “Bio-filtration” and “UV/PCO/Plasma” streams, and the collection-based category can be separated into the “Chemical Scrubbing”, “Cryogenic” and “Adsorption” streams. See Table 2 below.

Destruction-based methods	Collection-based methods
• Bio-filtration • UV/PCO/Plasma	• Chemical Scrubbing • Cryogenic • Adsorption

Table 2 *Categorisation for treatment methods*

7.3.3 The VOC removal performances, based on this detailed categorisation, are shown in Figure 11 below, which contains the same data set as Figure 8. It can be seen that the majority of the destruction-based methods adopted UV/PCO/Plasma, whilst most collection-based methods adopted surface adsorption. Chemical scrubbing, cryogenic condensation and bio-filtration methods are found in less numbers with a VOC removal rate of approximately at least 80%.

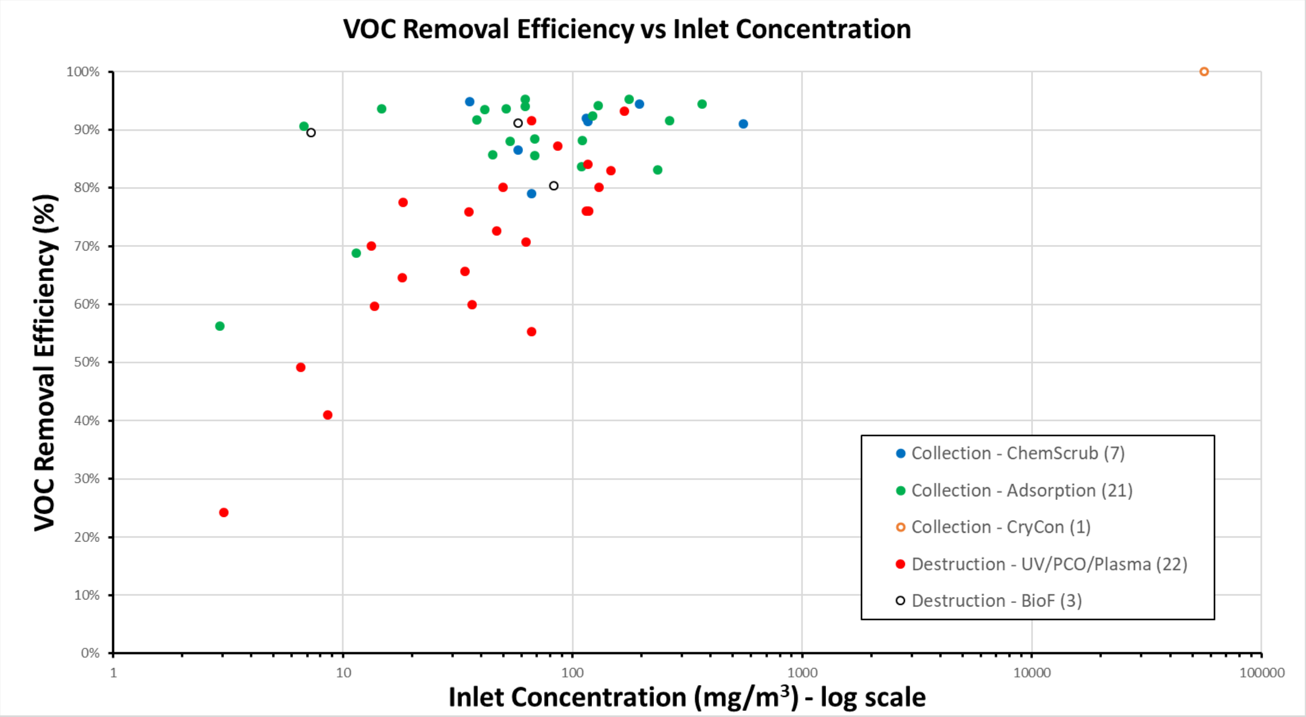

Figure 11 *VOC removal efficiency vs inlet concentration by treatment methods*

7.4. Removal Efficiencies vs Inlet Concentrations – Adsorption & UV/PCO/Plasma

7.4.1 This section focuses on the two major collection and destruction-based treatment methods of adsorption and UV/PCO/Plasma. Figure 12 below displays the two methods under the inlet concentration of 200 mg/m^3.

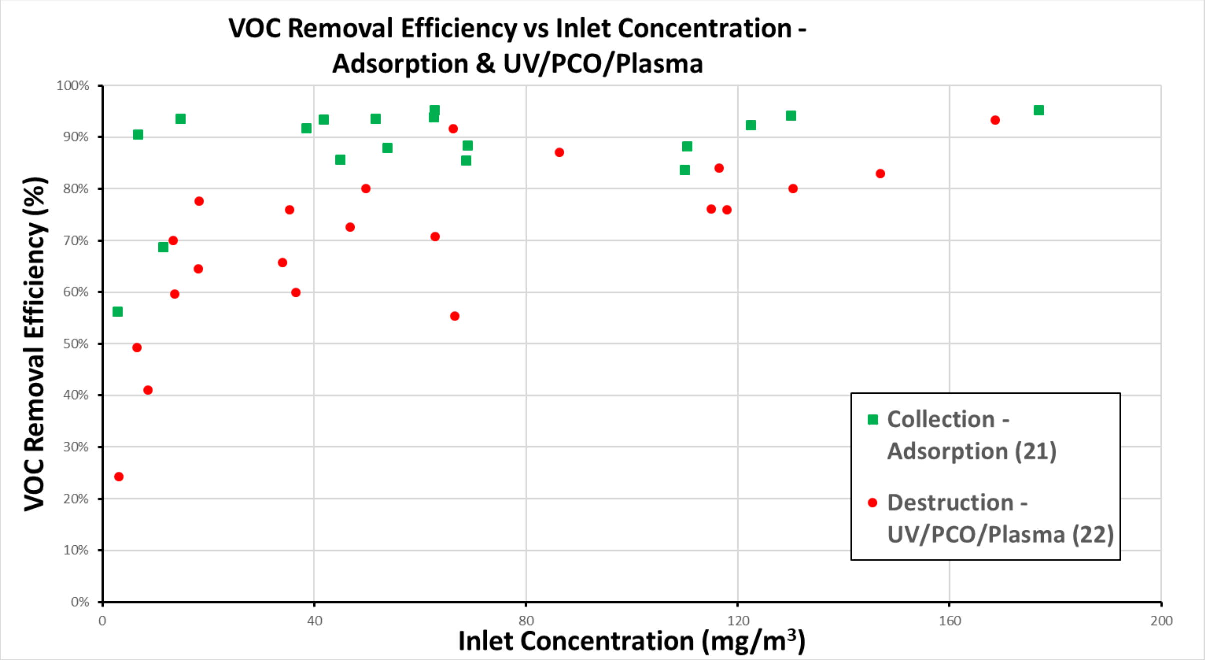

Figure 12 *VOC removal efficiency vs inlet concentration (Adsorption & UV/PCO/Plasma)*

7.4.2. A number of observations can be made based on the graph:

- Under low VOC concentrations, the adsorption treatment methods were able to generally maintain a high VOC removal rate (90%) compared to the destruction-based methods.
- The UV/PCO/Plasma methods, in comparison, had exhibited a sharper decrease in VOC removal efficiency when the VOC concentration is low.
- For the DP with the lowest removal efficiency (24%) at the lowest inlet concentration (3 mg/m^3), at the far left of the graph, refer to detailed explanations in section 7.2.3.

7.5. Removal Efficiencies vs Inlet Concentrations – Bio-filtration & Chemical Scrubbing & Cryogenic Condensation

7.5.1 A comparison of removal efficiency between chemical scrubbing, cryogenic condensation and bio-filtration is shown inFigure 13 below.

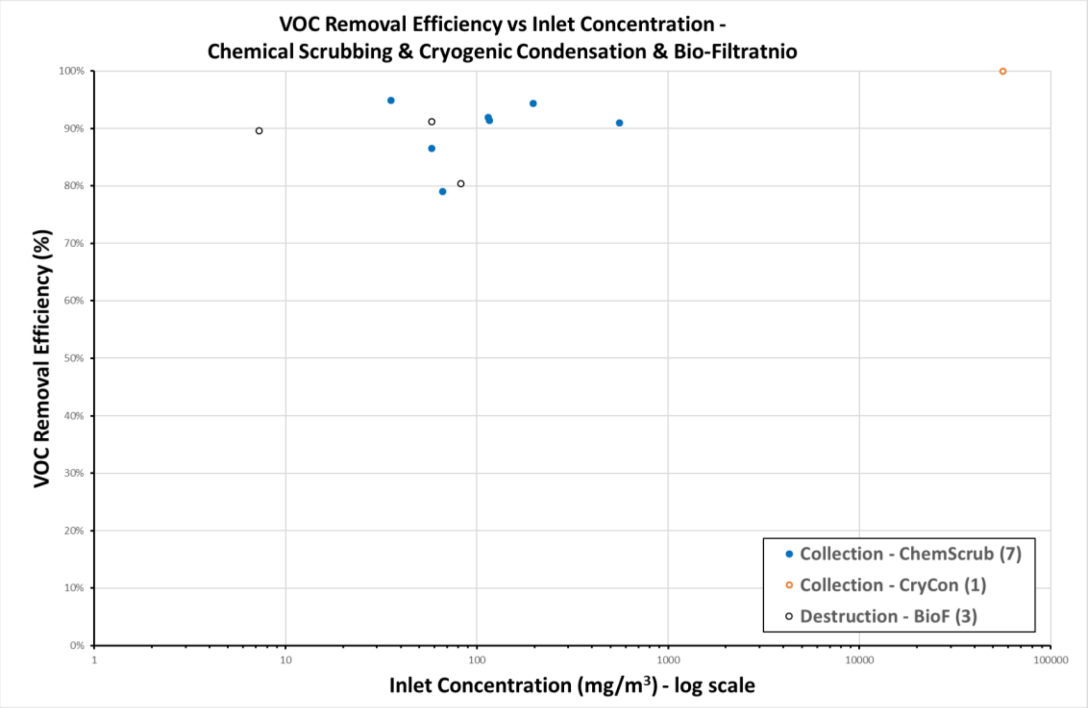

Figure 13 *VOC removal efficiency vs inlet concentration (Chemical Scrubbing & Cryogenic Condensation & Bio-filtration)*

7.5.2 A number of observations can be made based on the graph:

- Both the bio-filtration and chemical scrubbing methods had achieved at least 80% removal efficiency across the range of inlet VOC concentrations.
- Cryogenic condensation achieved the highest VOC removal of near 100% at a very inlet VOC concentration (56500 mg/m^3). There is only one DP associated with this method.

7.6. Investment Cost per Waste Gas

7.6.1 The second performance indicator, introduced in Chapter 4 as HKD per m^3/hr, compares the VOC treatment equipment cost with the actual amount of inlet waste gas that was treated. In other words, it provides a frame of reference for one to estimate how much initial investment is required in order to treat the VOC emissions at a certain scale of industrial operation using a particular VOC treatment technology. Note that cryogenic condensation, used by one DP, is an outlier value excluded from the figure due to its high investment cost per treated gas ($7,400 per m^3/hr). See Figure 14 below.

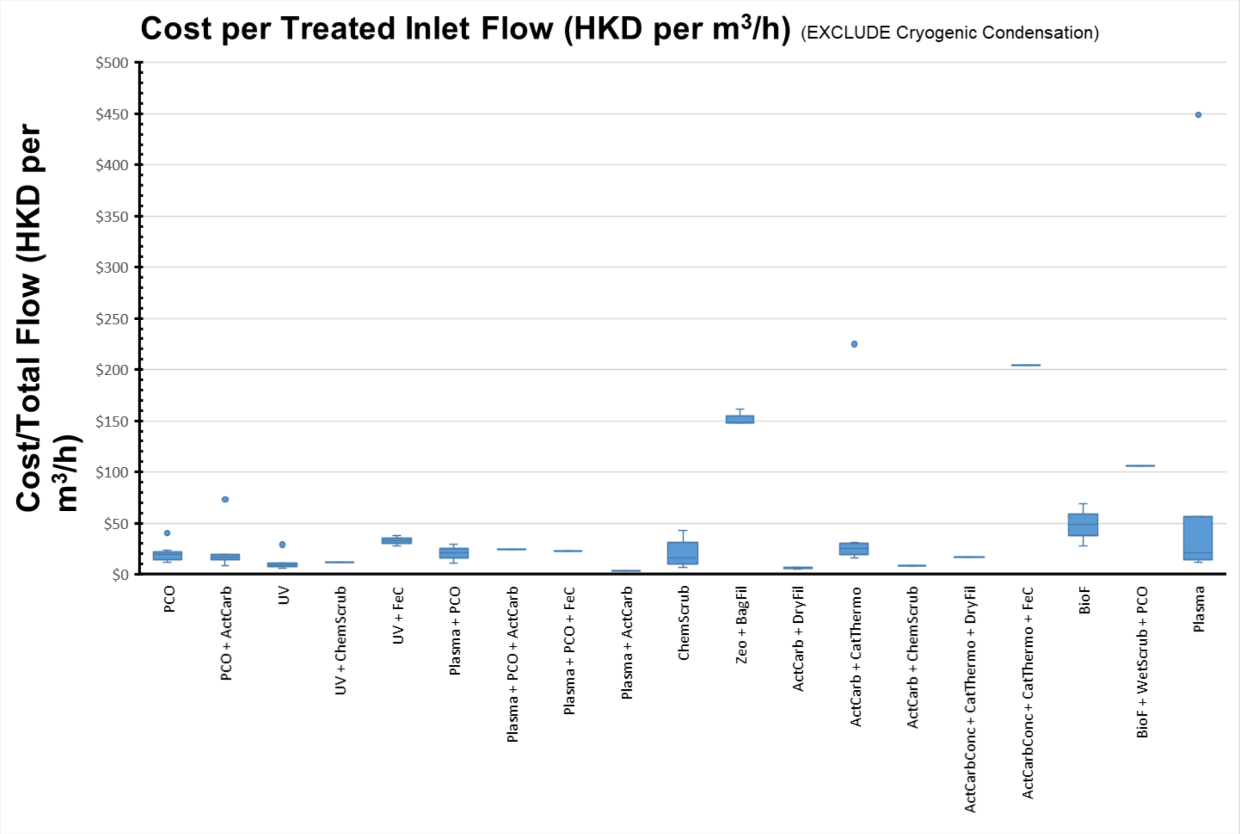

Figure 14 *VOC removal efficiency vs inlet concentration (Bio-filtration & Chemical Scrubbing)*

7.6.2 If the outlier data point from "low temperature plasma" is discarded, a more detailed comparison can be made for the remaining data set with the investment cost all under $250 per waste gas flow (HKD per m^3/hr). See Figure 15.

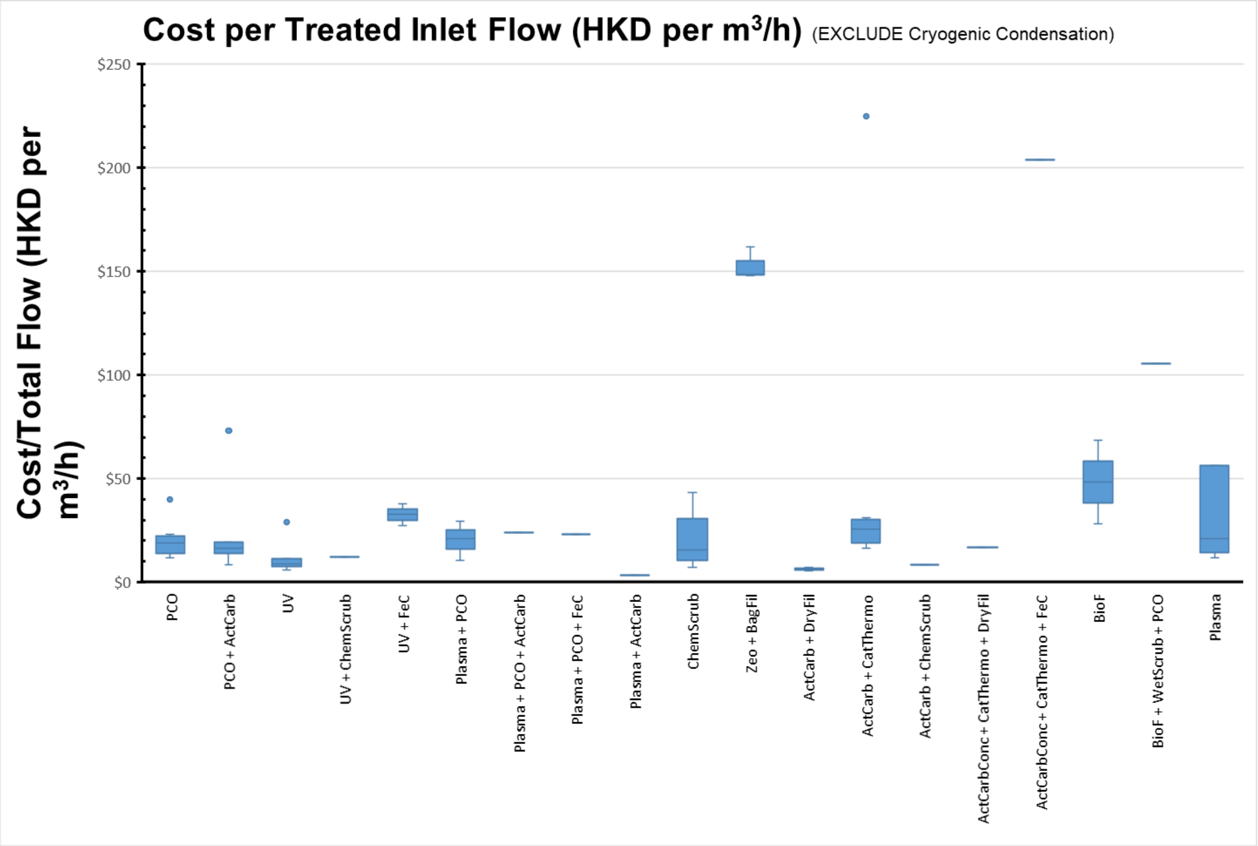

Figure 15 *Investment cost per treated gas volume (no cryogenic cond.)*

7.6.3 A number of observations can be made based on the graph:

- By deriving the initial investment cost to treat one cubic meter of waste gas flow per hour, a normalized comparison can be made to analyse the economic cost for various VOC treatment methods
- About 85% of the DP applications (46 out of 54) require less than $100 to treat one cubic metre of waste gas per hour. In terms of the highest median costs amongst these 46 DPs, bio-filtration is the most expensive at $48.4/m^3/hr, followed by UV-photocatalytic oxidation + iron-carbon micro-electrolysis at 32.6/m^3/hr and activated carbon + catalytic thermal oxidation at $25.5/m^3/hr; and
- Cryogenic condensation, associated with one DP application, has a very high initial investment cost compared to all other technologies.

8. SUMMARY OF FINDINGS

8.1 This study has been conducted to analyse the performance of the VOC treatment technologies in different aspects and performance indicators, including the range of inlet VOC concentrations, type of treatment technologies, removal efficiencies and investment cost. The main results of this study can be summarized as follows:

8.1.1 Industrial processes and inlet VOC concentrations

- The main industrial process by which VOCs are emitted are paint spraying (44%), printing processes (32%) and plastic melting (17%); and
- The median values of VOC concentrations found in the typical industrial processes are 96 mg/m^3 for paint spraying, 52 mg/m^3 for printing, and 45 mg/m^3 for plastic melting.

8.1.2 VOC concentrations and removal efficiency

- There is a general positive trend between the inlet VOC concentration and the removal efficiency, with removal efficiencies achieving above 70% for inlet concentrations over 80 mg/m^3;
- At the lower range of the inlet concentration (under 40 mg/m^3), there is a marked drop in removal efficiencies due to the condition of high flow rate with low concentrations that further dilutes the VOC concentrations;
- The adsorptive treatment methods that use activated carbon or zeolite as the primary treatment units are able to generally maintain a high VOC removal rate around 84-95% across the entire range of VOC concentrations;
- The destruction-based methods such as UV degradation, in comparison, exhibit a lower removal efficiency (24-77%) under low VOC concentrations (< 40 mg/m^3), whereas they achieve a generally higher removal of 74-93% at VOC concentrations greater than 40 mg/m^3;
- The chemical scrubbing and bio-filtration systems are able to maintain at least 80% VOC removal efficiency across the whole range of VOC concentrations; and
- About 85% of the DP applications (46 out of 54) require less than $100 to treat one cubic metre of waste gas per hour.

8.1.3 Initial investment cost and waste gas flow

- About 85% of the DP (46 out of 54) require less than $100 to treat one cubic metre of waste gas per hour;
- In terms of the highest median costs amongst these 46 DPs, “bio-filtration” is the most expensive at $48.4/m^3/hr, followed by “UV-photocatalytic oxidation + iron-carbon micro-electrolysis” at 32.6/m^3/hr and “activated carbon + catalytic thermal oxidation” at $25.5/m^3/hr; and
- Cryogenic condensation, associated with 1 DP, has a very high initial investment cost compared to all other technologies.

9. Conclusion

9.1 Based on the study findings, the treatment method of adsorption via activated carbon/zeolite, amongst the other methods, is able to guarantee a steady and high VOC removal rate of 84-95% across different VOC concentrations. However, due to the nature of the treatment, the sorbent media (e.g. activated carbon filter bed) would eventually be saturated with the collected VOC compounds, leading to breakthrough and loss of performance.

9.2 In order to reduce the direct VOC removal load of the adsorption unit and delay its saturation, the following options were generally adopted:

(a) In consideration of VOC treatment technologies, the inlet VOC concentration is an important factor. For treating low VOC concentrations (under 40 mg/m^3), the use of collection-based treatment methods are expected to maintain sufficient VOC removal at around 84-95%. For treating higher VOC concentrations, both collection and destruction-based treatment methods are capable of delivering high VOC removal up to 90% and higher.

(b) To use a combination of treatment technologies with destruction-based methods such as UV/photo-catalytic oxidation adopted as the first component of the treatment system, followed by adsorption treatment.

(c) When an adsorption unit of VOC is in place, use of a catalytic oxidation unit as an online system to regenerate the adsorption unit onsite, by purging the VOC compounds stored in the unit and oxidising them to maintain the performance and elongate the lifespan of the adsorption unit.

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Hong Kong Productivity Council

November 2019