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THESIS

VOLATILE ORGANIC COMPOUNDS REMOVAL BY BIOFILTER MADE FROM WASTEWATER SLUDGE

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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This study is to determine the efficiency of biofilter in which it was made from wastewater sludge mixed with shredded peanut shells, for toluene removal from air contamination. The ratios of the sludge to the peanut shells varied as 0 : 100, 30 : 70, 50 : 50, 70:30 and 100: 0 by volume. The mixture was added to a 2-L glass-tube with 10 centimeters diameter. Contaminated air contained toluene concentration of 42 – 420 ppmV flowed through the reactor with the air flow rate of 0.015 l/s. The residence time of 133 seconds were used in this study. The first periods of experiments were conducted for 2 weeks to acclimatize microorganisms and then the second period was continued for a month with the actual loading.

The toluene removal efficiency by the biofilter depends up on the volume of the wastewater sludge added in the reactors. It was found that in the reactor contained 30% 50% 70% and 100% of wastewater the concentration of toluene were removed about 57, 79, 94 and 96 %, respectively. When compare the elimination capacity of these reactors, the average elimination capacity of each reactor in the steady state, day 35 – day 45, was 22.52, 30.35, 36.51 and 37.19 g/m^{3}h respectively. There were 2 mechanisms founded in the biofilter. First was adsorption on peanut shell and second was biodegradation by microbial activities which indicated by CO_2 stripping. The biodegradation play important role in the biofilter because at the steady state the adsorption on peanut shell was already breakthrough.

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Jinchutar Srijohn
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LIST OF ABBREVIATIONS

CAAA = Clean Air Act Amendment
CCOHS = Canadian Center of Occupational Health and Safety
C/N = Carbon per Nitrogen ratio
EBRT = Empty Bed Resident Time
eV = Electron volt
g = Gram
HONs = Organic Hazardous Air Pollutants
Hr = Hour
IARC = International Agency for Research on Cancer
IP = Ionization Potential
l = Liter
mEq = Milliequivalent
ml = Milliliter
mmHg = Millimeter of Mercury
mMol = Millimol
mol = Mole
MTBE = Methyl Treachery Butyl Ether
NOx = Oxide of Nitrogen
PCD = Pollution Control Department
ppmV = Part per million by volume
PVC = Polyvinyl Chloride
S = Second
TCE = Trichloroethylene
US.EPA = United State Environmental Protection Agency

VOLATILE ORGANIC COMPOUNDS REMOVAL BY BIOFILTER MADE FROM WASTEWATER SLUDGE

INTRODUCTION

Volatile organic compound or VOC is one of the most environmental issues for local and national government, communities and non-government organization. Industrial section is one of the biggest VOCs emission sources that rapidly grow in the recent year. Several industries use VOCs as the raw materials such as the chemical industrial or is a solvent for production process. Although VOCs are not currently shown in the criteria pollutants, they are photochemically reactive and harmful. VOCs react with nitrogen oxides in the presence of sunlight to form ground level ozone and can also be a precursor to the formation of secondary particulate (Hunter and Oyama, 1955). Some VOCs can cause odorous nuisance and can have adversely affected to human health. Moreover, some VOCs are carcinogen or suspected carcinogen.

Toluene is an aromatic compound, which widely used in several industries. In 2007 the Pollution Control Department (PCD) has studied about the VOCs production and consumption in 457 chemical and petrochemical companies. It was found that 179,000 tons of toluene were produced and 173,511 tons were consumed. Toluene consumption is the seventh largest compounds from 47 types of interested VOCs. Toluene is classified as one of organic hazardous air pollutants (HONs) (Louvar, 1998). Inhalation of air with high toluene concentration can affect nervous system, liver and kidney.

Although there is limited national regulation of VOCs from the point source, the VOCs problem is highly concerned and should be reduced as low as possible to protect the worker health, people surrounding industry and also the environment.

There are several treatment methods for VOCs including activated carbon adsorption, absorption, biodegradation, condensation and incineration. To select the method for VOCs removal, the characteristic of the contaminated air such as air flow rate, pollutant concentrations and physical and chemical properties of the pollutants should be considered as well as the capital and operating cost.

Biofiltration is one of the most common methods that could give the low capital and operating cost. Biofiltration is also suitable for removal of VOCs due to its ability to degrade VOCs by a biological process with low VOCs concentration. This study intended to use the wastewater sludge from the wastewater treatment plant of the petrochemical process mixed with shredded peanut shells as the filter media for toluene removal. This study would explain the toluene removal mechanism occurring during the biofiltration.

OBJECTIVES

1. To determine the toluene removal efficiency by using the biofilter produced from various mixtures of wastewater sludge and shredded peanut shell.

2. To study the mechanisms related to toluene removal by biofiltration process.

Scope of This Study

This study was focused on the toluene removal efficiency and the elimination capacity of toluene removal by various proportion of wastewater sludge obtained from the petrochemical wastewater treatment plant and shredded peanut shells. The experiments were conducted in laboratory scale reactors. Toluene concentrations in the contaminated air used were generated from the vapor generator set. The experiments were operated for 45 days. For the first period of the experiments or about 15 days, it was done continuous to make sure that the microorganism can be acclimatized with toluene compounds then the experiments were operated for 30 days by adding the actual toluene loading. During acclimatization phase, toluene concentration was added through the biofilter with the concentration of 50 – 150 ppmV and then the toluene concentrations were changed to 150 - 300 ppmV and 300 - 400 ppmV, respectively. Toluene concentration was analyzed by using photo ionization detector which expressed the of total VOCs concentration (part per million by volume; ppmV) in terms of isobuthylene. From total VOCs concentrations, it was converted to toluene concentration by using the respond factor of the meter.

LITERATURE REVIEW

1. Volatile Organic Compounds

Title I of the Clean Air Act Amendment (CAAA) defines the volatile organic compounds or VOCs as any compounds containing carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate which participates in atmospheric photochemical reactions.

The United States Environmental Protection Agency (US.EPA) give the definition of VOCs as organic compounds having vapor pressure exceeding 0.1 millimeters of mecury (mm Hg) at standard conditions (20 °C and 760 mm Hg). VOCs include a variety of chemical compounds, some of which may have short- and long- term adverse health effects. VOCs or hydrocarbon can react photochemically with oxide of nitrogen (NO and $NO_{2,}$ collectively termed NO_x) in the presence of sunlight to form ozone nitroderivertives of organic compounds such as formaldehyde. The nitro compounds can react with moisture in the air to form the colloidal dispersion known as smog. (Bishop, 1998)

2. Toluene

Toluene is one of aromatic hydrocarbon which consists of benzene ring and methyl group, sometimes it is called methyl benzene. The molecular weight of toluene is 98 g/g-mol. Normally it is a clear liquid with aromatic smell, and water-insoluble liquid. Toluene is present at low level in crude oil and is usually produced in the processes of making gasoline via a catalytic reformer, in an ethylene cracker or making coke from coal. Toluene is used for fuel blending to increase octane value, used as the substrate to produce benzene, phenol, toluenedisocyanate, etc. or used as the industrial solvent. Figure 1 show the molecular structure of toluene.

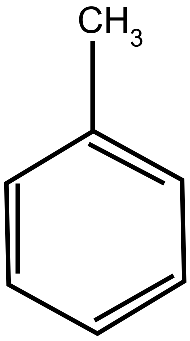


Figure 1 Molecular structure of toluene

Toluene is classified as one of Organic Hazardous Air Pollutants (HONs) (Louvar, 1998)The International Agency for Research on Cancer (IARC) has determined that there is inadequate evidence for the carcinogenicity of toluene in humans. However, inhalation of toluene at high concentration (at 10,000 ppm) can damage the central nervous system and cause unconsciousness or death. If contact with toluene by swallow or get in to the eyes or skin, it will irritate the contacted organs. (Canadian Center of Occupational Health and Safety : CCOHS, 1997)

3. Volatile Organic Compounds Control Technique

There are several techniques to control VOCs emission from industrial process not to exceed the standard or within acceptable limit. Among those conventional technologies, combustion, carbon adsorption, condensation, absorption and biofiltration, the efficiency and cost for each technique are quite varied. Industries should investigate the source of VOCs emission and find the most appropriate alternative to eliminate or control the VOCs emission in the acceptable value. Figure 2 show the guideline to choose appropriate control technology.

Those techniques are suitable for some ranges of contamination and gas flow rate. Moreover the economical data and the operation are also considered to select for use in gas treatment (Hunter and Oyama, 1955; Shareefdeen and Singh, 2005)

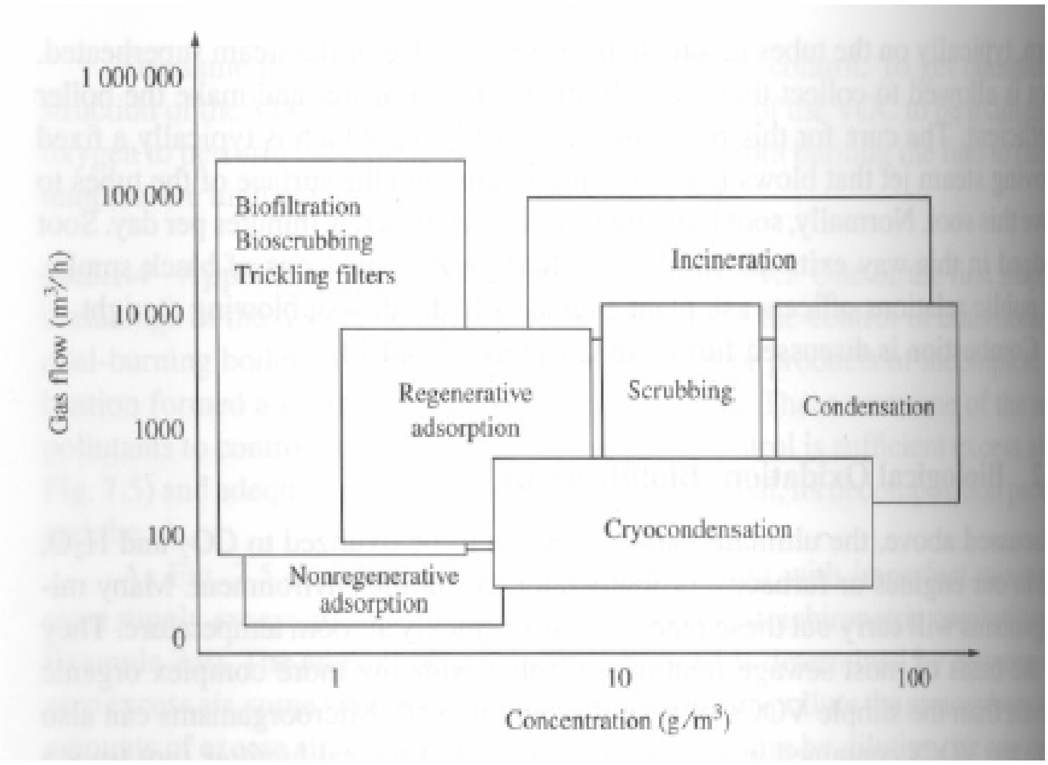


Figure 2 Guideline to select VOCs control technologies, based on flow rate and concentration only.
Source: de Nevers (1995)

3.1 Condensation

Condensation is the liquid fraction of condensable contaminants by the use of low temperature. The contaminants are removed from the gas stream at the temperature which their partial pressure in gas stream exceed their dew point.

3.2 Adsorption

Adsorption is to contain the contaminants on the surface of material. This technique is typically used to remove the contaminants in low concentration from gas stream by passing through the high-surface area material such as activated carbon.

3.3 Absorption

Absorption is a physical process consisting of the dilution of contaminants in a liquid. The gas stream is introduced to the chamber counter current with the liquid. The contaminants are removed from air stream to liquid stream. Henry's law is used to determine the equilibrium of the mixture in gas and liquid stream.

3.4 Thermal incineration

Thermal incineration has been considered to be the most effective control device for VOCs for many years. The contaminated stream is burned at high temperature. Efficiency of the device sometimes is high as 98%. But the high amount of energy is required. Sometimes catalyst is added in the process to reduce the activation energy than gas-phase combustion. This process is known as catalytic incineration.

3.5 Biological treatment

Biological treatment is the degradation of contaminant by using microorganism. The microorganisms grow on a media or are suspended in the reactor. The biofilter is good for removal of low concentration contaminated stream.

3.6 Membrane separation

Membrane technology uses the semi-permeable membranes to separate the contaminants from gas stream. This method is effective for chlorinated hydrocarbons, chlorofluorocarbon, and hydro fluorocarbon.

3.7 Ultraviolet treatment

Ultraviolet is used to oxidize the organic compounds. This technique is about 99% effective in destruction of organic compounds. But it required a large cost for the contaminated air with high flow rate and low photo efficiency.

4. Biofiltration

The biofiltration is one of an interesting alternative. Devinny *et al.*(1999) indicated that the bioreactor had been used in United State and Europe for over 50 years to control the odor from wastewater treatment plant. Bioreactor is recommended to control volatile organic compounds especially those stream with low VOCs concentration and high volume flow rate because of following reasons

1) Removal efficiency for Hazardous air pollutant is over 90%

2) Low operating cost.

3) Require small quantity of energy.

4) Low chemical usage.

5) Less space required and multiple units can be run in parallel

However, biofilters have some disadvantages such as

1) Biofilter cannot treat some VOCs which have low adsorption or degradation rates. Especially for the chlorinated VOCs.

2) The fluctuate source of emission can causes some damage to the microbial in biofilter.

3) Some biofilter may take a long period to adjust the condition for microbial living.

The biodegradability of various contaminants in biofilter is shown in table 1.

The biological degradation is carried out particularly by bacteria. The degradation process consists of a few steps using enzymes and catalyst specific for each step. The biological degradation process occurs by oxidation in the biofilter, and can be written as follows (Anit and Robert, n.d.)

$$\text{Organic Pollutant} + O_2 \rightarrow CO_2 + H_2O + \text{Heat} + \text{Biomass} \qquad (1)$$

4.1 Bioreactors

Biofiltration can be categorized into several types which different applications as following

4.1.1 Biofilter

The biofilter allow contaminated air pass through the filter bed which contain the microorganisms. The microorganisms grow on the surface of the moist-packed media or support material and create the bioflim around it. Before entering the reactor the air has to be moistened then it can pass through the reactor upward or downward. Sometimes the water spray is needed to maintain the moisture of the system. The scheme of biofilter is shown in figure 3

Table 1 Biodegradability of various contaminants in biofilter.

Contaminant	Biodegradability	Contaminant	Biodegradability
Aliphatic hydrocarbons		**Sulfur-containing carbon compounds**	
Methane	1	Carbon disulfide	2
Propane	Not Available	Dimethyl sulfide	2
Butane	Not Available	Dimethyl disulfide	2
Pentane	1	Methyl mercaptan	1
Isopentane	1	Thiocyanates	1
Hexane	2	**Oxygenated carbon compounds**	
Cyclohexane	1		
Acetylene	1	Alcohols	3
Aliphatic hydrocarbons		Methanol	3
Benzene	2	Ethanol	3
Phenol	3	Butanol	3
Toluene	3	2-Butanol	3
Xylene	2	1-Propanol	3
Styrene	2	2-Propanol	3
Ethylbenzene	3	Aldehydes	3
		Formaldehyde	3
Chlorinated hydrocarbon		Acetaldehyde	3
Carbon tetrachloride	1	Carbonic acids	3
Chloroform	1	Butyric acd	3
Dichloromethane	3	Vinyl acetate	2
Bromodichloroethane	Not Available	Ethyl acetate	3
1,1,1-Trichloroethane	Not Available	Butyl acetate	3
Vinyl chloride	1	Methyl ethyl ketone	3
1,2-Dichlorobenzene	Not Available	Ketones	3
Chlorotoluene	1	Acetene	3

Source: Devinny *et al*.(1999)

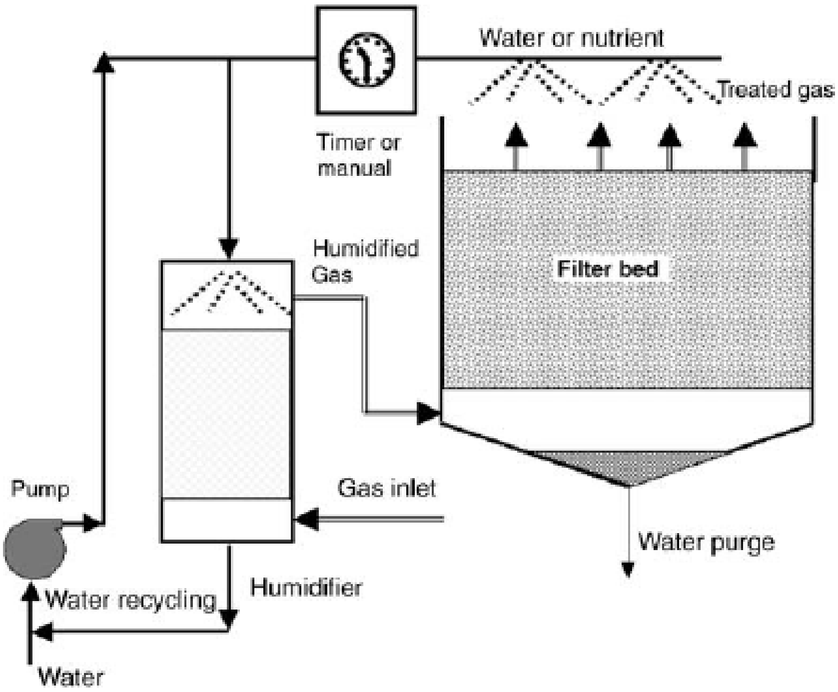


Figure 3 Schematic of open bed biofilter.
Source: Shareefdeen and Singh (2005)

4.1.2 Biotrickling Filter

In the biotrickling filters, the contaminated air passes through a packed column while the liquid is recirculated through the bed continuously as shown in figure 4. The contaminants will absorb in the liquid film and transfer to the microorganisms which growing on the surface of support material

4.1.3 Rotating Biological Contactor

The rotating biological contactor is similar to the one used for water treatment. The biofilim will form on the discs which mounted on a rotating shaft. The discs are partially wetted in water containing nutrients and additives.

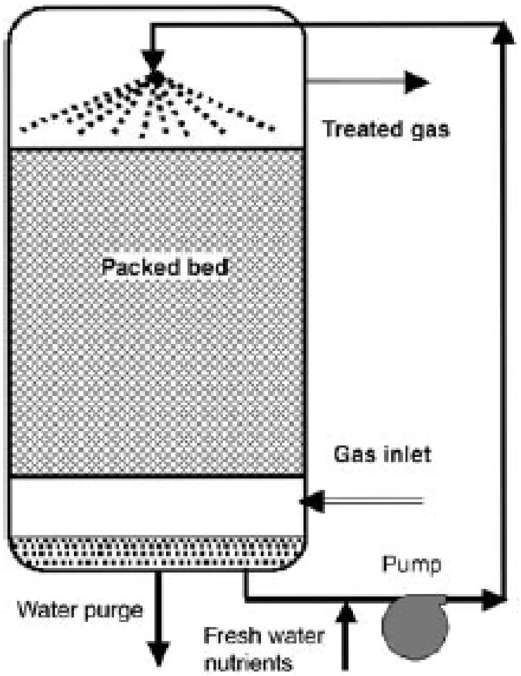


Figure 4 Schematic diagram of a biotrickling filter.
Source: Shareefdeen and Singh (2005)

4.1.4 Bioscrubber

In bioscrubber, the contaminant is removed by adsorption in the liquid stream which re-circulate continuously. The microorganism suspended in the liquid with supplementary oxygen and contact to the contaminated air stream in the reactor. The schematic diagram of bioscrubber is shown in figure 5

4.1.5 Membrane Bioreactor

The typical membrane bioreactor is the hollow fibers and flat sheet. It allows the microorganism to attach on the shell side and the contaminated air passes through the lumen of the tube. The membrane can be constructed with several materials and has different chemical and physical properties.

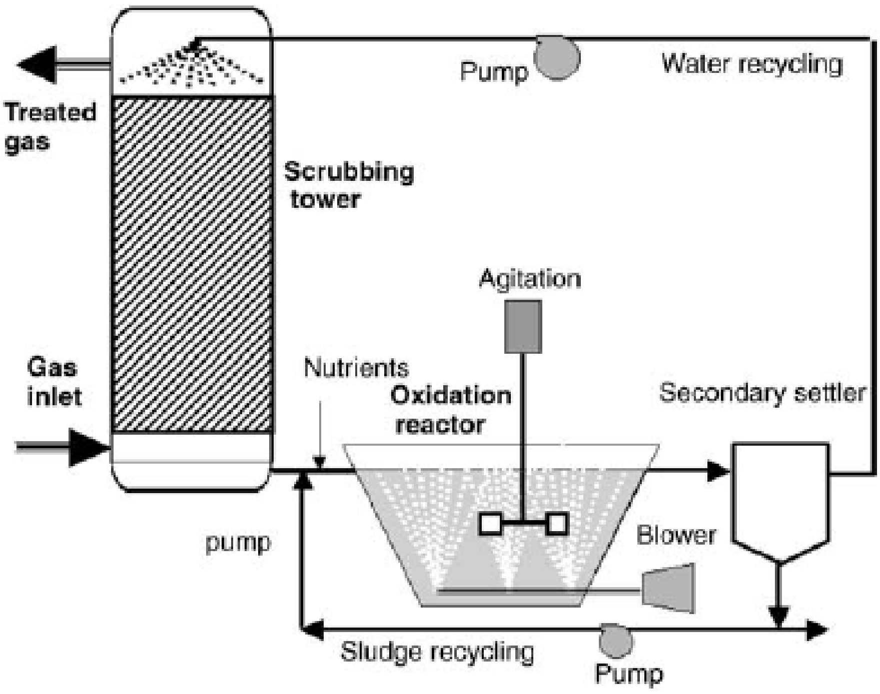


Figure 5 Schematic diagram of a bioscrubber system
Source: Shareefdeen and Singh (2005)

4.1.6 Suspended Cell Bioreactor

In the suspended cell bioreactor, the microorganisms are suspended in the liquid as shown in figure 6. The contaminated air is bubbled in the bulk of the liquid. The system should be designed to optimize mass transfer from the bubble to bulk liquid where biodegradation occurs.

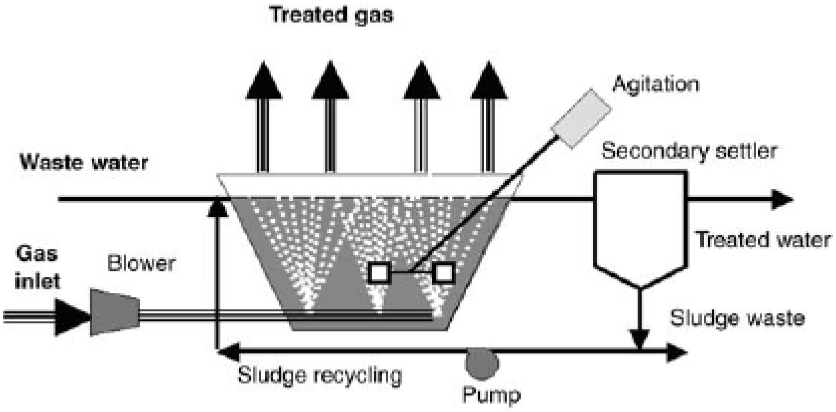


Figure 6 Schematic diagram of a suspended growth bioreactor

Source: Shareefdeen and Singh, 2005

Table 2 show the classification of several biofiltration reactor

Table 2 Classification of biological reactors

Biomass	Liquid phase	Reactor
Fixed on a support	Stationary	Biofilter
Fixed on a support	Flowing	Biotricking Filter, Ratating Contactors
Suspended	Flowing	Bioscrubber
Suspended or fixed	Stationary	Suspended Growth
Fixed on a membrane	Flowing	Membrane

Source: Shareefdeen and Singh (2005)

4.2 Mechanism of Biofiltration

There are some mechanisms occur in biofilter during treatment of contaminated air stream. Understanding each step will help in controlling the biofilter. The first of the treatment process is transferring of the contaminant from air stream to water phase then adsorb on the bioflim or onto the microorganism cells or even the support medium. And the biodegradation by cells metabolism will transform the contaminant to water and carbon dioxide or metabolic-by product. (Devinny *et al.*,1999)

4.2.1 Transfer of contaminant

The contaminants in air can move to water phase around the support medium according to Henry's Law. The contaminant in water phase and air phase will be proportional as describes by Henry's Constant in equation 2

$$C_G = HC_L \qquad (2)$$

Where C_G = the concentration of contaminant in the air phase, atm or g L_{air}^{-1}

H = the Henry Law's constant, dimensionless

C_L= the equilibrium concentration of contaminant in water phase, mol L_{water}^{-1} or g L_{water}^{-1}

The Henry's Law constant typically lower that 1 therefore the concentration in air usually lower than in water. (Devinny *et al.*, 1999) The higher Henry's Law constant is also higher in elimination capacity because the contaminant is tending to partition in the liquid or biofilm phase where degradation occurs. (Shareefdeen and Singh, 2005) Henry's Law constant depends on temperature and the chemical potential of the liquid phase. Table 3 show the Henry's Law constant for some compounds in water at 25 °C

On the interface of water and air, the stream flow laminar. The molecular diffusion presents here and is the rate-limiting factor for mass transfer because the molecular diffusion slower than the advection. But in bioreactor, the air flow quickly

Table 3 Henry's Law constant for some compounds at 25 °C

Compounds	**Henry's Law constant (non-dimensional)**
Hexane	30.9
Hydrogen Sulfide	0.92
Toluene	0.25
Benzene	0.22
Methyl iso-butyl ketone	0.016
Ethanol	0.0012

Source: Shareefdeen and Singh (2005)

So the laminar layer between air and water is quite thin. The transfer in this layer is not the limitation in most case. According to two-film theory, the rate of mass transfer can be calculated by following equation.

$$\frac{dC_L}{dt} = k_t (C_L^e - C_L) = k_t \left(\frac{C_G}{H} - C_L \right) \qquad (3)$$

When C_L = the concentration of the contaminant in bulk water

C_L^e = the concentration of the contaminant at equilibrium with local air concentration

T = time

k_t = transfer rate constant, per unit time also equal to K_La,where a is the interfacial area

K_L = The overall mass transfer coefficient

Even the different compounds have the different constant, the amount of mass transferred is proportional to the surface area because the fundamental factor is the surface-to-volume ratio.

The mass decreased in air phase equal the mass increased in water phase but the concentration is different because of the different on the volume of air and water When the mass transfer rates are assumed to be uniform, k_t is constant, the model can be simplified as following

$$\frac{dC_G}{dt} = -k_t \frac{V_L}{V_G}(C_L^e - C_L) \qquad (4)$$

Actually, the determination of transfer rate is difficult because of the effect of biodegradation and the mass partition coefficient. Anyway the mass partition coefficient can be measure in pulse test. And the biodegration can minimize by adding the inhibitor. Under these conditions, measurements of the output pollutant during the breakthrough condition can estimate the transfer rate coefficient. (Devinny *et al*., 1999)

4.2.2 Contaminant Adsorption

The contaminant which is not solute in water phase can be adsorbed on the medium surface, on the biofilm of organic matter or within the organic matter in the biofilm or medium as shown in figure7. Adsorption is the major reservoir for the hydrophobic compounds. (Devinny *et al*., 1999)

To understand the adsorption mechanism, Freundlich and Langmuir model are used to describe. The freundlich model assume that sites for adsorption are not limited and the amount of contaminant held depend on the concentration in the water. The increasing of the liquid phase concentration will increase the amount of contaminant adsorbed. The freundlich isotherm can shown in following equation

$$C_{ads} = k_f C_L^{1/n} \qquad (5)$$

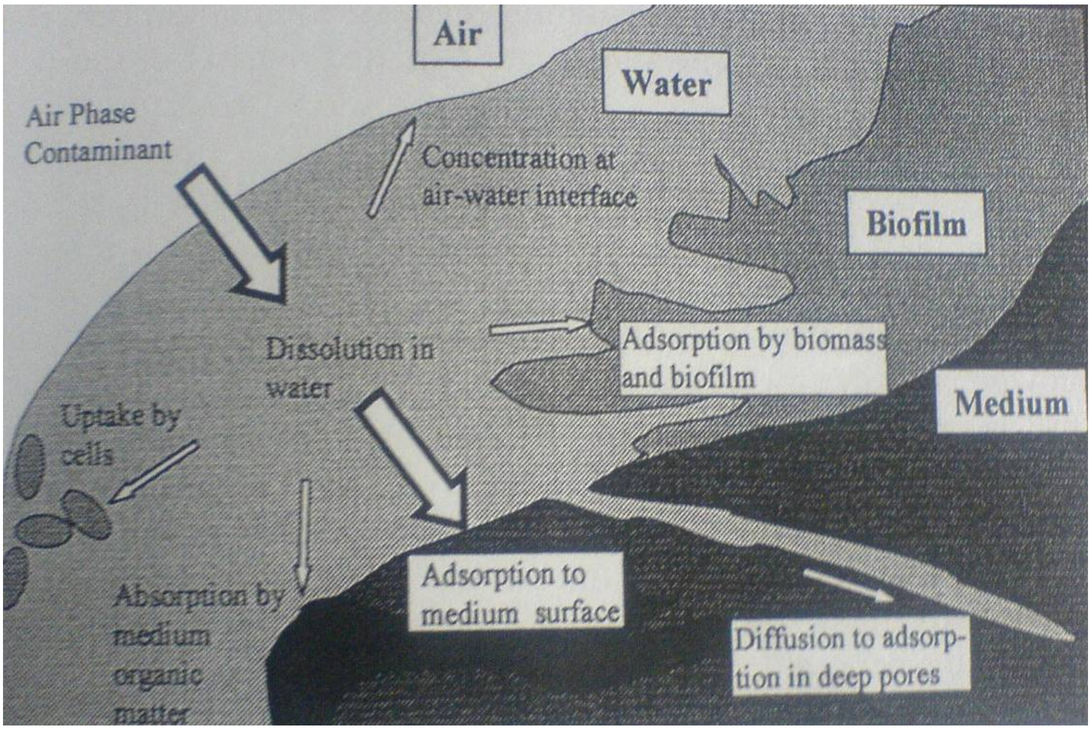


Figure 7 Adsorption in biofilter

Source: Devinny *et al*. (1999)

Where C_{ads} = concentration of adsorbed contaminant

C_L = concentration in the liquid phase

k_f = Freundlich adsorption constant

The Langmuir Isotherm assume the sorption sited is limited and can be described by equation 6

$$\text{Cads} = \frac{C_{max} C_L}{k_L + C_L} \tag{6}$$

Where C_{max} = the maximum concentration when all sited are occupied

C_L = concentration in the lliquid phase

k_L = The langmuir adsorption constant

Devinny *et al.* (1999) reported that when the concentration in liquid phase is high, the sorption site will be occupied and the amount of the contaminants adsorbed will be a constant independent of concentration

The medium of biofilter can be the buffer for concentration of contaminant changing because the adsorption capacity is the function of the concentration in the air in many cases. If the concentration in the air is drop, the contaminants can be released from the sorption site. However, adsorption and adsorption do not take place instantly and may be very fast, the system are always near equilibrium.

The adsorbed contaminant will be able to biodegrade if the ecoenzymes are released by the microorganism and degrade to the desorbed products.

4.2.3 Biodegradation

Biodegradation is the key of contaminant removal in biofilter. The bioflim on the medium will metabolize the contaminant into non toxic product and by product. Biodegradation can be explained by kinetic model, Michelis-Menten which developed for enzyme mediated reactions

$$\frac{dC_L}{dt} = \frac{k_{max} C_L}{K_S + C_L} \tag{7}$$

Where C_L = Contaminant concentration in liquid, mol L^{-1}
k_{max} = maximum degradation rate, mol L^{-1} s^{-1}
K_s = half-saturation constant, mol L^{-1}

The Michaelis-Menten kinetic model in figure 8 assumes that the number of microorganism is not change. The concentration is proportional to the rate of degradation until it is as high as with respect to the half saturation constant, the biodegradation rate is near the k_{max} and constant independent from concentration. (Devinny *et al.*, 1999)

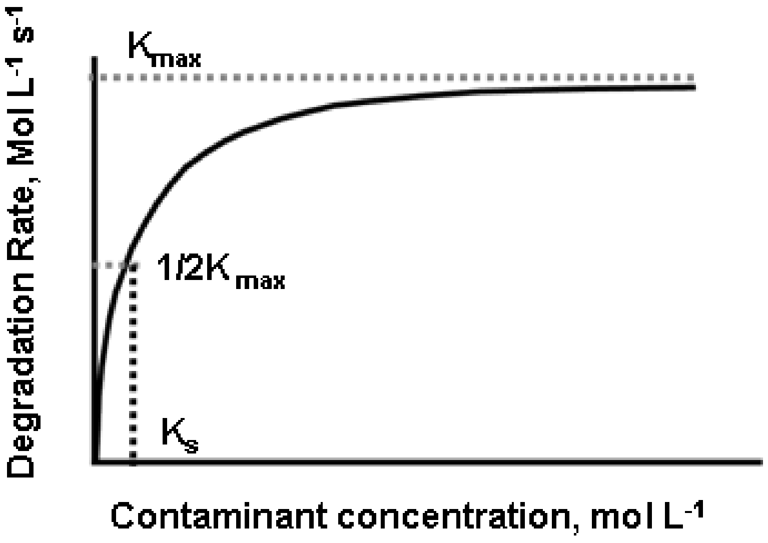


Figure 8 Michaelis-Menten kinetic model
Source: Devinny *et al*. (1999)

The Monod model can describe the rate at which biomass is expected to grow. The coefficient of proportionality or growth constant depends on the concentration of contaminant. The growth is proportional to the size of microbial.

$$\mu = \frac{\mu_{max} C_L}{K_s + C_L} \tag{8}$$

And

$$\frac{dX}{dt} = \mu X \tag{9}$$

Where μ = the coefficient of proportionality, specific growth rate, s^{-1}

μ_{max} = maximum cell growth, s^{-1}

K_s = half-saturation constant

X= density or concentration of biomass, mg L^{-1}

From the model, at high concentration of contaminant ($C_L >> K_s$) growth will achieve μ_{max} but, at low concentration ($C_L << K_s$), growth is the first order reaction which the rate of reaction depends on the concentration. (Shareefdeen and Singh, 2005)

4.2.4 Product from reaction

Simpler organic and inorganic compound can be degraded by microorganism and convert to carbon dioxide, water, sulfate, nitrate or secondary product . While the complex or difficult-to-degrade compound have several transformations by several types of microorganisms as shown in figure 9. Some intermediate compound with high vapor pressure can escape from the biofilter but some which can be degraded will accumulate in the biofiter or release with the leachate. Some of carbon in the compounds can be used for incorporated into cells synthetic process. The difference between the amount of degraded and carbon dioxide released can indicated how much the carbon is being incorporated in biomass. (Devinny *et al.*,1999)

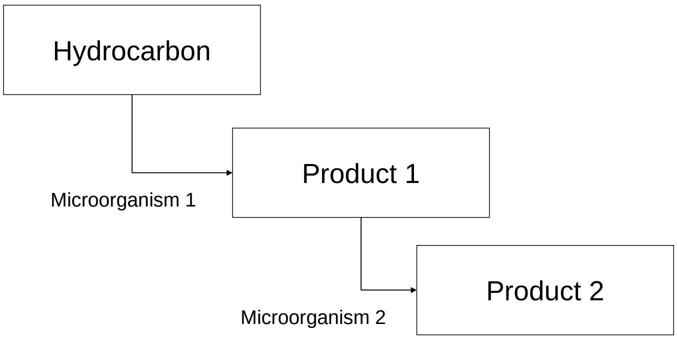


Figure 9 Biotransformation and transport process in biofilters
Source: Devinny *et al.* (1999)

Mineralization occurs when the contaminant is completely oxidized. It requires stoichiometics amount of oxygen to undergo. But sometimes partial oxidation may produce when the oxygen is insufficient as shown in table 4.

Tabel 4 Example of biological reaction.

Type	Example
Growth	C + H +N + S + P + minerals → biomass
Mineralization with oxygen	$C \rightarrow CO_2$ $S \rightarrow SO_4$ $N \rightarrow NO_3^{-1}$ $H \rightarrow H_2O$ $R\text{-}Cl \rightarrow CO_2 + HCl$
Partial oxidation	Ethanol → CO_2 + acetaldehyde + acetic acid + ethyl acetate Isopropanol → acetone 1-propanol → propianaldehyde → propionic acid Sulfide → elemental sulfur → sulfite
Cometabolism	MTBE in the presence of linear alkanes TCE in the presence of methane or phenol Benzene in the presence of toluene, ethylbenzene and xylenes

Source: Shareefdeen and Singh (2005)

When the organic compounds are oxidized, some heat is generated. The heat generated can be measure to indicate the degradative activities. In unsteady state biofilter, the temperature of filter bed may increase but in steady is may not. The heat generated will become noticeable by the evaporated water from filter bed or increasing of outlet air temperature. The water can evaporate from the filter when the temperature rising and both of the inlet and outlet air has 100% humidity. This evaporation takes place because the water content of warmer air is higher. The amount of heat required for evaporation can be calculated from the heat of evaporation of water.

4.3 Controlled Parameter of Biofilter

Biofilter is easily to operate and has low operating and maintenance cost. However understanding the keys concerned of its operation will help the biofilter reach maximum contaminant elimination capacity and prolong the lifetime of the system. In order to operate the biofilter efficiently, controlling of these parameter in the optimum range is required.

4.3.1 Water content

Moisture content in the medium is the most important parameter used to operate the biofilter because the microorganism will active under the optimum moisture content. Therefore, this parameter is affect the transfer of contaminant from the air and the physical properties of the medium.

1) Water in porous media and the thermodynamic

According to the polar characteristic of the solid, water can be sorped to the surface of the medium than those in air which is non-polar molecule. When the water is added to the medium, a dry porous medium faces with the water vapor and it will have the strong tendency to suck the water molecule from the air. Now the individual water molecule of water is adsorbed on the surface of the medium. But the water chemical activity will be quite low on the surface of dry medium as shown in figure 10.

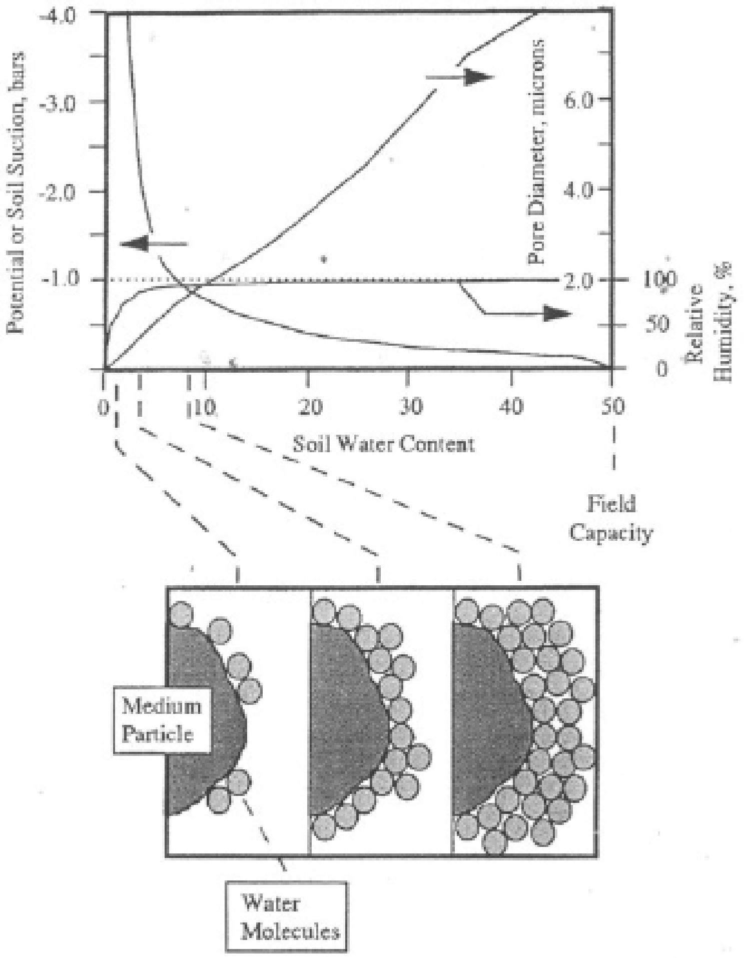


Figure 10 Water activities, soil suction, and threshold pore diameter in porous media.
Source: Devinny *et.al* (1999)

First, this activity is controlled by the strength of the attraction of water molecule to the adsorption surface. When the surface is more occupied, the water can be less adsorbed and more released. Therefore the equilibrium relative humidity rises but always below 100%. The amount of water required to fill a surface in monolayer is depended on the surface area of medium. The surface area is the important parameter to the relationship among water activity, medium moisture content, relative humidity and biological availability of water. When the monolayer is complete, the water molecule will be added on other water molecules. The humidity of the pure water at the equilibrium with water molecules sticking onto other water molecule is 100%. But in the porous media, the humidity will not rise to 100% because of 2 reasons. First, the polar of the support material will polarized the water molecule in the second layer adsorbed on it. This attraction can occur over several water layers if it is strong enough. Second, the water layer is not flat. The water molecule is under the attractive force form the water below and to the sides. If the water layer is convex, the attractive force will less because the water molecules on its side are drawn back. On the other hand, if the water layer is concave, the attractive force is increase because of surrounding water molecule as shown in figure 11. The concave surface can hold the molecule better than the convex surface and as a result of the less water activity (chemical potential) and is at the equilibrium with a lower vapor pressure.

At equilibrium, the individual water molecule always evaporates and condenses constantly. Also the water molecule in the pore of media is at equilibrium at the same vapor pressure. The water in the larger pore always evaporate and condense in the smaller one until the water in the large pores are empty except for the layer held by the adsorption and the small pore are full. The pore with a radius of curvature smaller than the thermodynamic equilibrium value for the water will be filled with the water. The equilibrium water radius is known as the threshold pore radius. The pore radius is important for operating the biofilter. If almost the large pores are filled, anaerobic conditions may occur and the air flow will be slowed down. But if the water is held only by the small pores inadequately, the microbial activities will be inhibited

The chemical potential or water activity are used to determine the strength which the molecules are held in the soil water by the mineral surface or by others water molecules as shown in the equation below.

$$\varphi = \frac{RT \ln a_w}{10V_w} \tag{10}$$

Or

$$\ln a_w = \frac{10 V_W \varphi}{RT} \tag{11}$$

Where φ = water potential or soil suction, bars

R = gas constant = 8.314 J mol^{-1} K^{-1}

a_w = water activity = relative humidity 10-2

V_w = partial molal volume of pure water = 0.018 L mol^{-1}

The water activity is the ideal thermodynamic concentration and related to the relative humidity. Pure water is assigned the activity 1.0, potential = 0 , and the air over it is at the relative humidity of 100% . The water which hold tightly by attraction to the porous media surface has a potential less than 0 because it require some energy to move to the body of pure water, its activity is below 1 and the relative humidity is below 100%. The potential can be called “soil suction” or “soil water tension” and can be measured in the unit of pressure.

The relationship between water potential and the curvature of the water surface in the pores is examined as below

$$r_w = \frac{20\gamma}{\varphi} \tag{12}$$

Where r_w = equilibrium water radius or threshold pore radius, cm

γ = the water surface tension, N cm^{-1}

For a dry material, the water activity is very low and the relative humidity is zero. At the high water content, the water activity is near 1.0, the relative humidity is near 100% and the attraction of the medium for the water is low so the water added always drains off. This condition is called “field capacity”, where the soil suction is weaker than the gravity of force, which the biofilters are operated near this value.

The characteristic curve of each porous media depends on the surface composition, surface area, and pore size distribution. This curve is the relation between water content and water potential. Figure 11 shows the theoretical curve where the relative humidity and the threshold pore diameter displayed in a function of water content. The water potential is high when the medium is very dry and is zero when it reaches field capacity.

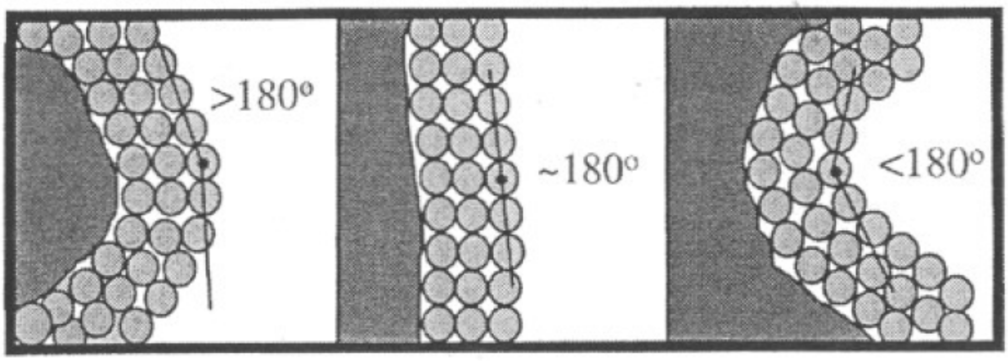


Figure 11 Effects of surface curvature on the water film.
Source: Devinny *et.al* (1999)

2) Biological and partition effect

The soil suction is one important parameter for the activities of microorganism. They cannot live under the condition that soil suction greater than their limit. The high soil suction causes the high energy required to draw water molecule into the cell and the cell growth will reduce. Water in cells in necessary for cell metabolism, dissolve chemicals and also is the medium in cells. Therefore the cells have to control their water content. Metabolism in cells will reduce the substrate and increase the waste concentration in their surroundings. Because the diffusion in water is slower than in air, the microbial in the pore filled with water and in the biofilm may get the substrate and oxygen difficulty and face the high concentration of the waste product. Biofilter may include a film of standing water around the biofilm. If the water content in the biofilter increases, the water film expands thicker than the biofilm. Microorganism can live in this water so the biofilter can maintain communities of the free organism.

The organic compound in air stream can be adsorbed in following ways (Devinny *et al*, 1999)

a) Vapor adsorption onto solid surface

b) Vapor condensation in micropores (only when the medium is very dry)

c) Detachment onto solid organic matter, likely occurs for compost media.

d) Dissolution into adsorbed water films

e) Adsorption to the gas-liquid interface

The biodegradation of the contaminants will take place in the water or while adsorbed onto the support media. The compound which easily to solute in water will presents as high concentration in water phase. If the water is provided in high amount, the contaminants will dissolve better and more opportunity for decomposition.

4.3.2 Temperature

Control of temperature in the optimum range for the microorganism is one of the key factors for successfully operate the biofilter. Microorganisms can survive and effective in an appropriate range of temperature. Though the reaction increase when the temperature rise, it should be not over the limit of those microorganisms. Cell components such as enzyme and membrane can be destroyed if the temperature is over the range. Figure 12 show the temperature effect on microorganism. Each species can survive in the different range. In the biofilter, several species of microorganism are developed. If the temperature changes rapidly, some species might not active except for those which can tolerate. Most of the biofilters are operate in the warm temperature because if the gas temperature changes rapidly, the thermophilic and phychrophillic could be inhibited. In the other hand, in most gas the Henry's law coefficient increase with the temperature so less compound can dissolved in the water. This phenomenon affects less adsorption in biofilter. But the bioreaction is more important in biofilter than the physical reaction so the warm temperature is acceptable.

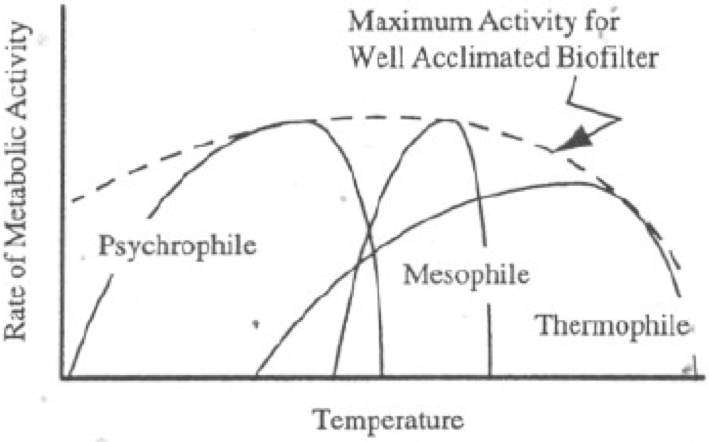


Figure 12 Temperature effect on species of microorganism and biofilter activities.
Source: Devinny *et.al* (1999)

4.3.3 pH and alkalinity of the medium

pH and alkalinity are like temperature. There are an optimum range for operating the biofilter. Most of biofilter are design to operate at pH 7, neutral, because very high or low pH can destroy some species of microorganism. The pH in reactor may change during operation. Some intermediate products which low pH may develop to non-acidic products in the final. Buffer capacity is the parameter used to determine the ability of the medium to resist the pH change. The higher buffer capacity of the medium related to the higher resistance for pH change. Inorganic media may have low buffer capacity. The buffer capacity can be defined as the amount of hydrogen ion needed to change the pH. As describe by following equation

$$\beta = \frac{dC_B}{dpH} \tag{13}$$

Where β = Buffer capacity

C_B = added acid of base

Buffering materials such as calcium carbonate may be added to the media in order to control the reactor upset. Calcium carbonate will neutralize the acid generated, therefore the pH will remain constant.

4.3.4 Contaminant load and surface load

Contaminant load is the mass of contaminant entering the biofilter per unit time per volume. The contaminant load in biofilter range from a few part per billion to thousands part per million (less than 1 $g/m^3/h$ to more than 100 $g/m^3/h$). The removal efficiency of biofilter is high when loads are low. Because high load may causes the acidification of the medium. The reactor with low load may reach approximately steady state with respect to biomass and nutrients. The microorganisms are starving and will consume the biomass produced. Clogging may take place in bioreactor with high load because biomass will grow rapidly under nutrient rich condition. Biomass which causes clogging in the reactor has to be removed. And the nutrients have to be added to replace those were removed with the biomass stream.

The contaminated stream with high concentration in low surface load will be treated more effectively. The higher concentration of contaminant in the biofilm is produced and also the speeding biodegradation if the biokinetics are higher than zero order.

4.3.5 Oxygen limitation

Qxygen limitation means the concentration of oxygen which affects the rate of biodegradation. Oxygen gas-liquid partition is 33.5 means most of oxygen prefer to be in gas phase than dissolved. For example, at 25 °C the dissolved oxygen concentration in equilibrium with air is about 8.1 mg/l or 0.253 mMol. (Devinny *et.al*, 1999) The oxygen diffusion coefficient in water is about 2.1×10^{-9} m^2/s while VOC diffusion coefficients are in the range of 0.8 to 1.3×10^{-9} m^2/s. These value are not much different therefore there are assumed identical. Therefore if the stoichiometric amount of oxygen demand is larger than 0.253 mMol, the oxygen will be exhaust in the biofilm before the VOCs is treated. Lack of oxygen causes partially oxidized by-products such as carboxylic acids or aldehydes. (Devinny *et.al*, 1999) The minimum of VOCs concentration that causes oxygen limitation are shown in table 5

4.3.6 Nutritional

In order to reach the desired performance level of the biofilter, sufficient nutrient to the system is required because the biodegradation take place in the biofilter by the microorganisms which need the nutrients for growth and activity. Nutrients may be naturally present in organic support material or already added in the synthetic support material. The minerals and trace metals needed for growth is N, P, K, S, Ca, Na, Mg, Mn, Fe, Co, Zn and Mo. More detail is shown in table 6. The biomass yield also depends on the nature of nutrient. Some biofilter can intake the nutrients to the system by spraying the nutrient solution to the filter bed.

4.4 Design of Biofilter

To design the biofilter in a field work, there are some terminology used to design and operate the biofilter as describe following. (Shareefdeen and Singh, 2005)

Table 5 Estimated threshold concentration for oxygen limitation of treatment of VOCs

Compond	**Amount of oxygen needed for complete oxydation**	**Lowest concentration of contaminant in the air to induce oxygen depletion in biofilm**[a]	**Maximum VOCs elimination capacity**[b]
		(g/m^3)	($g/m^3/h$)
Ethanol	3	0.0009	88
Ethyl Acatate	5	0.0245	110
Toluene	9	0.7112	64
Hexane	7.5	195	65

[a] Calculate assuming complete aerobic oxidation; oxygen and VOCs diffusion coefficient to be identical; a temperature of 20 to 25 °C

[b] Assuming an oxygen transfer rate of 200 $g/m^3/h$

Source: Devinny, *et al* (1999)

4.4.1 Empty Bed Residence time

The empty bed residence time or EBRT is used to estimate the size of reactor. EBRT is the empty bed volume divided by airflow rate.

$$\mathrm{EBRT} = \frac{V}{Q} \tag{14}$$

Where V = Empty bed volume, m^3

Q = Air Flow rate, m^3/s

Table 6 Important nutrient required for the growth and activity of microorganisms.

Nutrient	**Nutrient Source**
Nitrogen	Ammonium Sulfate, Ammonium Nitrate, Ferrous Ammonium Citrate
Phosphate	Dipotassium hydrogen phosphate, Potassium dihydrogen phosphate
Mineral	Magnesium Sulfate, Calcium Chloride, Ferrous Sulfate
Trace Metals	Zinc Sulfate, Cobalt Chloride, Manganese Chloride, Copper Sulfate, Ferric Chloride, Sodium Molybdate, Borate, Nickel Chloride
Vitamins	Nicotinic acid, Ca-pentothenate, Cyanocobalamine, Inositol, *p*-aminobenzoate, Thaimine-HCl Pyridoxine-HCl, Biotin, Riboflavin, Folic acid, Thioctic acid

Source: Shareefdeen and Singh (2005)

The empty bed residence time is an over estimating of the contact time but easily to calculate. The actual resident time can be calculated by multiply the EBRT with the bed porosity.

$$\pi = \frac{V}{Q} \times \theta \tag{15}$$

When π = true resident time, second or minute

θ = porosity = volume of void space / volume of filter material

4.4.2 Surface loading, Volumetric loading and Mass loading

All of these terms used to define the amount of air being treated. Surface loading rate it the volume of air per unit area of filter material per unit time. The volumetric loading rate is the volume of air per unit volume of filter material per unit time. Both parameters is indicated as following.

$$\text{Surface Loading} = \frac{Q}{A} \tag{16}$$

$$\text{Volumetric Loading} = \frac{Q}{V} \tag{17}$$

The mass loading rate is the mass of contaminant entering the filter per unit area (or unit volume) per unit time. The mass loading will decline along the filter because some is removed along the distance. However, the general overall mass loading is defined as following.

$$\text{Mass Surface Loading} = \frac{Q}{A} \times C \tag{18}$$

$$\text{Mass Volumetric Loading} = \frac{Q}{V} \times C \tag{19}$$

When C = Concentration of contaminant, g/m^3 or ppm

4.4.3 Removal Efficiency and Elimination Capacity

Both terms are used to illustrate the performance of biofilter. The removal efficiency is the percentage of the contaminant fraction removed by the biofilter. However it can not completely describe the performance of the system because the performance is varies with the contaminant concentration, air flow and biofilter size while the elimination capacity normalize the volume and flow rate. So the elimination capacity is better to compare the result of the different biofilters.

$$\text{Removal Efficiency} = \left(\frac{C_{in} - C_{out}}{C_{in}} \right) \times 100 \tag{20}$$

$$\text{Elimination Capacity} = \frac{(C_{in} - C_{out}) \times Q}{V} \tag{21}$$

$$\text{Elimination Capacity} = \text{Volumetric mass loading} \times \text{Removal Efficiency} \tag{22}$$

Elimination capacity can be equal or less than mass loading. At low mass loading rate, the elimination capacity is usually equal the mass loading rate and the removal efficiency is 100%. But when the mass loading is increased, the elimination capacity will reach its critical value where the mass loading rate exceed the elimination capacity. If the mass loading is still increased, the elimination capacity will reaches its maximum point called the maximum elimination capacity as shown in figure 13 . For biofilter treating common pollutants, the elimination capacity is around 10 – 300 g m^{-3} h^{-1} (Devinny *et al.*, 1999)

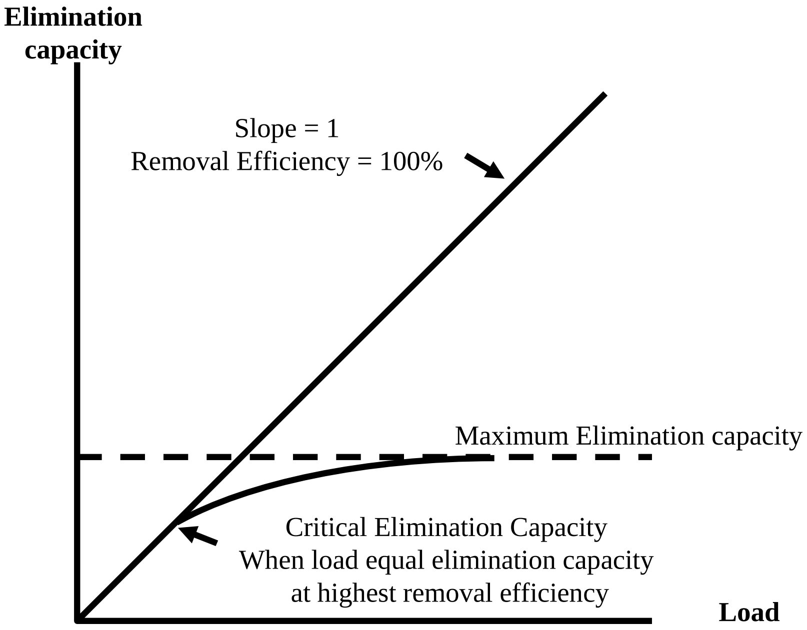


Figure 13 Typical elimination capacity and load curve.
Source: Devinny *et a.l* (1999)

The typical of biofilter operating condition is described in the table 7

There were several studies about VOCs elimination in the past. Jirawat and Wongpun, n.d studied the removal of acetone vapor by bench scale biofilter using 4 media as a mixture of biosolids soil, composted potting soil, compost and wood barks. The experiment varied the gas flow rate at 2.5, 3.0 and 4.0 liter per minute and acetone concentration ranged from 200-1,000 ppmV. The result showed that a mixture of biosolids soil, composted potting soil, compost and wood barks achieved the maximum elimination capacity of 97, 90, 120 and 83 g/m^3-hr

Arthit *et al*. (2007) studied to used granular activated carbon as the supporting material for bacteria *PseudomonasPutida* at air contaminated with benzene flow rate 200 ml/min and residence time at 46.977 seconds. The result showed that removal efficiency of inlet concentration at 50 ppmV was more than 99%.

Table 7 Typical Biofilter Operating Conditions for Waste Air Treatment

Parameter	**Typical value**
Biofilter layer height	1-1.5 m
Biofilter area	1-3000 m^2
Waste air flow	50-300,000 $m^3\ h^{-1}$
Biofilter volumetric loading	5-500 $m^3\ m^{-2}\ h^{-1}$
Bed void volume	50%
Mean effective gas residence time	15-60 s
Pressure drop per meter of bed height	0.2-1.0 cm water gauge (max. 10 cm)
Inlet pollutant and / or odor concentration	0.01-5 g m^{-3}, 500-50,000 OU m^{-3}
Operating temperature	15-30^{0}C
Inlet air relative humidity	>98%
Water content of the support material	60% by mass
pH of the support material	pH 6-8
Typical removal efficiencies	60-100%

Source: Devinny *et.al* (1999)

Vegana *et al.* (2007) studied about effects of gas flow rate, inlet concentration and temperature on the biofiltration of toluene vapors by biofilter using compost to support the microorganisms and sea shells to control the pH. It was observed that on increasing the toluene inlet load from 37 to 70 g/m^3 h the conversion by the biofilter varied by from 98% to 93%. The biofiltration system used achieved elimination capacities of up to 82 g/m^3h for a toluene load of 100 g/m^3h

Alvarez-Hornos *et al*. (2008) investigate suitable packing materials, a soil amendment composed of granular high mineralized peat for biofilter use to remove ethylbenzene. Maximum elimination capacity of about 120 g/m^3h for an inlet loading of 135 g/m^3h was obtained for the fibrous peat. The soil amendment reactor achieved a maximum elimination capacity of about 45 g/m^3h for an inlet load of 55 g/m^3h.

The result of previous study about Performance evaluation of a compost biofilter treating toluene vapors by Eldon R. Rene *et al*. (2004) was conclude that toluene removal efficiencies higher than 90% were achieved with an EBRT of 147 seconds and inlet concentrations less than 0.5 g m^3. A maximum elimination capacity of 128 g/m^3h was obtained at an inlet load of 263 g/m^3h

Mathur *et at*. (2007) studied about biofiltration of air stream containing mixture of benzene, toluene, ethyl benzene and *o*-xylene has been studied in a lab-scale biofilter packed with a mixture of compost, sugar cane bagasse and granulated activated carbon in the ratio 55:30:15 by weight at average inlet concentration of 0.4194 g/m^3 and at an empty bed residence time of 2.3 minutes. Biofilter achieved maximum removal efficiency more than 99% of all four compounds

MATERIALS AND METHODS

Materials

1. 5 sets of laboratory scale reactor consist of glass columns with10 cm diameter and 27 cm high outfitted with PVC pipe for inlet and outlet
2. Toluene vapor generator sets consist of liquid toluene 5 ml in closed-glass tube 5 sets connect with a fresh air pump to generate toluene vapor by flexible hoses.
3. Moisture vapor generator sets consist of distilled water 15 ml in closed-glass tube 5 sets connect with a fresh air pump to generate toluene vapor by flexible hoses.
4. Wastewater sludge from industrial activated sludge treatment plant
5. Shredded peanut shell
6. 2 M NaOH solution used for CO_2 stripping and 1 M H_2SO_4 used for titration, 5 sets
7. Hot wire anemometer
8. Photo ionization detector Model Phocheck 3000+
9. Total pore volume and specific surface area analyzer, Autosorb-1
10. Hot air oven and desigator for material weighing

Methods

1. Reactor preparation

The reactors were made from glass column 27 centimeter height and 10 centimeters in diameter outfitted with PVC pipe for inlet and outlet. The mixture of wastewater sludge and peanut shell 2000 milliliter was filled in the glass column. At the bottom of the column, a perforated acrylic plate was placed for the support and for the uniform distribution air. A sampling valve is outfitted with inlet PVC pipe for taking sample. Outlet pipe was connected to the Erlenmeyer flask containing 50 ml of NaOH solution for CO_2 stripping.

2. Media bed preparation

The sludge from a chemical industrial wastewater treatment plant was mixed with shredded-boiled peanut shell in various proportions. The mixture ratio was range from 0 : 100, 30 : 70, 50 : 50, 70:30 and 100: 0 by volume. These mixtures were separately added to each reactor. The mixture was prepared for 2,200 ml, 2,000 ml was filled in the reactor and additional 200 ml was for moisture and weight measurement before the experiment.

The properties of wastewater sludge and peanut shell in various ratios is showed in table 8

Table 8 Properties of the mixture in each experiment

Experiment	Peanut shell : Wastewater sludge (by volume)	Initial moisture content (%)
Experiment 1	100 : 0	11.32
Experiment 2	70 : 30	51.52
Experiment 3	50 : 50	63.50
Experiment 4	30 : 70	70.93
Experiment 5	0 : 100	78.00

3. Experimental Setup

The schematic of the experimental setup is shown in figure 14. The moisture of the medium was maintained by humidifying air stream to the biofilter. Moist air was generated by infuse fresh air to water tube.

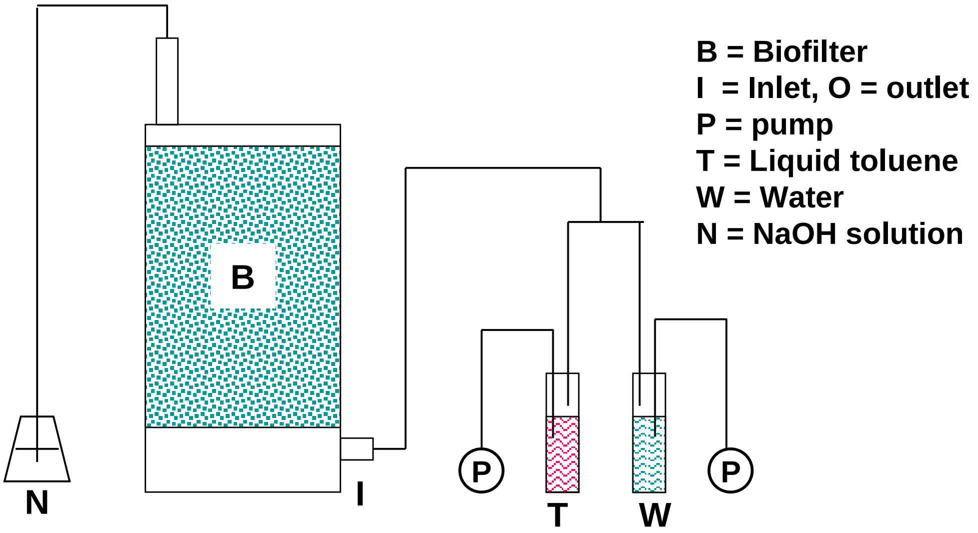


Figure 14 Schematic diagram of the experiment

The fresh air flow rate 9.1 ml/s was blew to 5 ml of toluene in cylinder glass tube to generate toluene vapor. The toluene vapor would fuse with moist air before entering the biofilter.

The acclimatization phase was conducted from day 1 to day 15 to acclimatize the microorganisms. The concentration of toluene was increased every 5 day. The range of toluene in day 1 – 5 was 42 to 92 ppmV, day 6 -10 was 155 – 292 ppmV and day 11 – 15 was 369 to 399 ppmV. In this phase, toluene was introduced to the biofilter 24 hours per day at 0.015 l/s flow rate and 133 seconds resident time.

The experiment phase started from day 16 to day 45 to determine the efficiency of biofilter for removal of toluene 366 – 420 ppmV at 0.015 l/s flow rate and 133 seconds resident time. In this phase toluene was introduce to the biofilter only 8 hours per day in order to simulate the actual working period in industry. After that moist air stream was continuously supplied through the reactors until the next day.

4. Study of the removal efficiency and mechanism in biofiter

The toluene concentration at inlet and outlet were analyzed by photo ionization detector. (Phocheck Model 3000+). The PID was calibrated weekly with standard gas, Isobutylene 100 ppm. Daily reading of the standard gas was also done to ensure the accuracy of reading value. To determine the concentration, the PID has response factor (RF) for each known substance specific with the model of PID and the ionization potential (IP) of the substance. Toluene has IP 8.82. The VOCs meter used in this study was 10.6 eV and the response factor for toluene 0.51 times of reading value. The actual concentration of toluene was 0.51 times of the reading value.

Outlet pipe was connected to Erlenmeyer flask containing NaOH and $BaCl_2$ CO_2 was collected as Na_2CO_3 which then react with $BaCl_2$ to form NaCl and $BaCO_3$ precipitate. This solution was titrated with H_2SO_4 and the end point indicated by phenolphthalein. The milliequivalent of NaOH remaining was determined by the amount of H_2SO_4 used.

The amount of Carbon dioxide generated is defined from following equations

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \tag{23}$$

$$Na_2CO_3 + BaCl_2 \rightarrow 2NaCl + BaCO_3 \tag{24}$$

From equation 23, CO_2 of 22 mg reacts with each millequivalent (mEq) of NaOH. The amount of CO_2 generated can be determined by equation 25.

$$\text{mg of } CO_2 = (\text{mEq of NaOH in solution} - \text{mEq of } H_2SO_4 \text{ used}) \times \left[\frac{\text{mg of } CO_2}{\text{mEq}}\right] \tag{25}$$

Table 9 show the summary of parameters controlled in the experiment. And experiment diagram is showed in figure 15.

Table 9 Summary of parameters controlled in the experiment.

Parameter	Unit	Typical*	Experiment
Inlet Concentration	g/m3	0.01 - 5	1.38 – 1.58 (366 – 420 ppmV)
Surface loading rate	m3/m2-h	5 – 500	6.75
Volumetric loading rate	m3/m3-h	5 - 500	26.5
EBRT	S	15 - 60	133

Source: * Devinny *et.al* (1999)

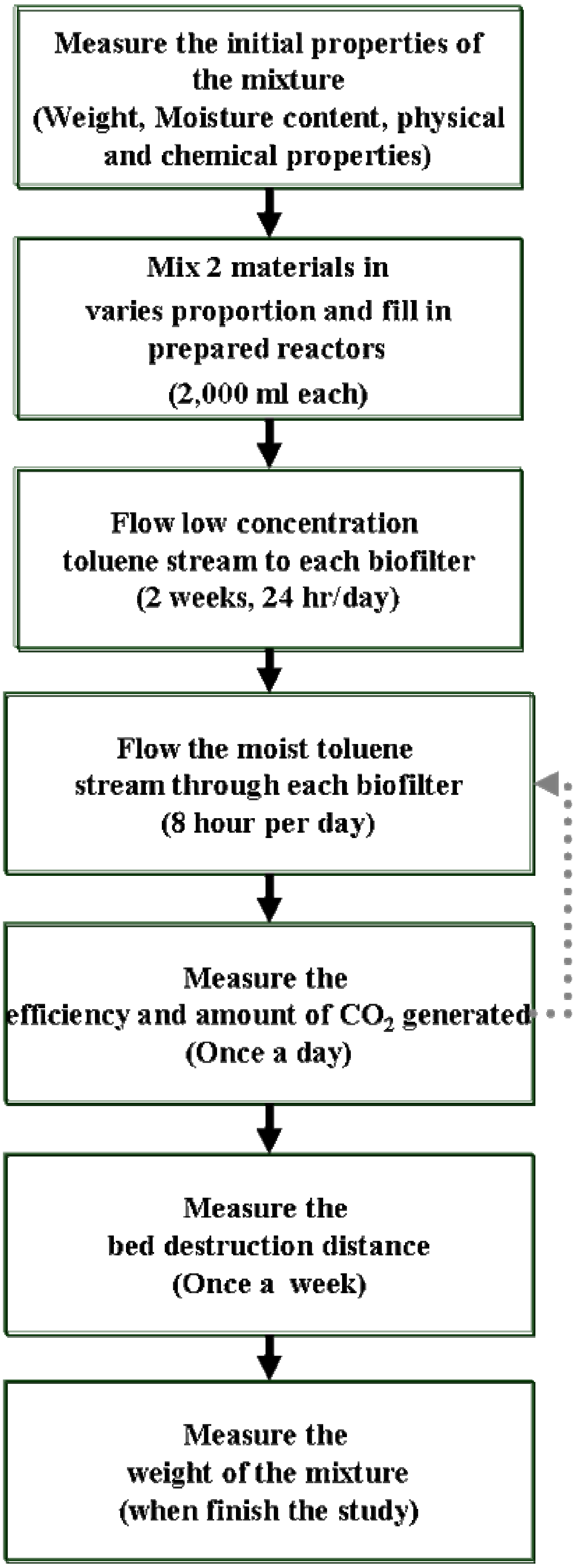


Figure 15 Diagram of the study

RESULTS AND DISCUSSSION

Results

1. Study of physical and chemical properties of wastewater sludge and shredded peanut shell

Drying sludge from the wastewater treatment plant and shredded peanut shells brought through the laboratory at the department of chemical engineering, Kasetsart University to determine the physical properties including the density and specific surface are. While the chemical property including the nutrient was analyzed at the department of soil, faculty of agricultural, Kasetsart University.

The result showed that the sludge from the petrochemical wastewater treatment plant had lower specific surface area than the shredded peanut shell but richer nutrient than the peanut shell. The higher value of specific surface volume, is greater in mass transfer coefficient. In general, for a compost-based media, an initial N, P and K in the range of 0.4, 0.15 and 0.15% by dry weight of packing is consider sufficient. (Devinny *et. al*, 1999) Therefore both wastewater sludge and shredded peanut shell contained optimal value for N, P and K for the biofiltration process. Result of physical and chemical properties of the wastewater sludge and shredded peanut shell is showed in table 10.

2. Study of the removal efficiency of each experiment

2.1 Removal Efficiency

The experiment 1, reactor with 100% peanut shell had efficiency above 90% from day 1 to day 29 . Then at day 30 the removal efficiency decreased to

Table 10 Physical and Chemical properties of the material

Parameter	Unit	Wastewater sludge	Shredded peanut shell
Density	g cm^{-3}	0.46	0.13
Specific Surface area	m^2 g^{-1}	0.84	25.62
	m^2 cm^{-3}	0.3864	3.3306
Moisture Content	%	78.00	11.32
N	%	7.47	1.53
P	%	0.42	0.14
K	%	0.1	0.75
Zn	%	0.41	0.015
Mn	%	0.04	0.086
Fe	%	1.00	0.487
Cu	%	0.57	0.015

28.40% finally at day 35 the removal efficiency was fall to 1.97%. To compare with other experiment the efficiency will be described in 3 stages, acclimatization phase, experiment phase 1, day 6 – 29, and steady state, day 35th – 45th. The overall removal efficiency is showed in figure 16

From figure 16 showed that the reactor with 100% peanut shell had almost constant removal efficiency in the acclimatization phase. While other reactors had the same behavior when compare the left 4 reactor, the removal efficiency increased with the percentage of wastewater sludge added in the biofilter. Further increase in inlet concentration of each reactor resulted in lowering the removal efficiency. However the removal efficiency could recover in later days.

During the experiment phase, before the peanut shell in the reactor with 100% peanut shell breakthrough, day 16 to day 29, it still maintain the removal efficiency at above 90%. The left reactors had average removal efficiency in experiment phase increasing with the percent of wastewater sludge. However, the removal efficiency in

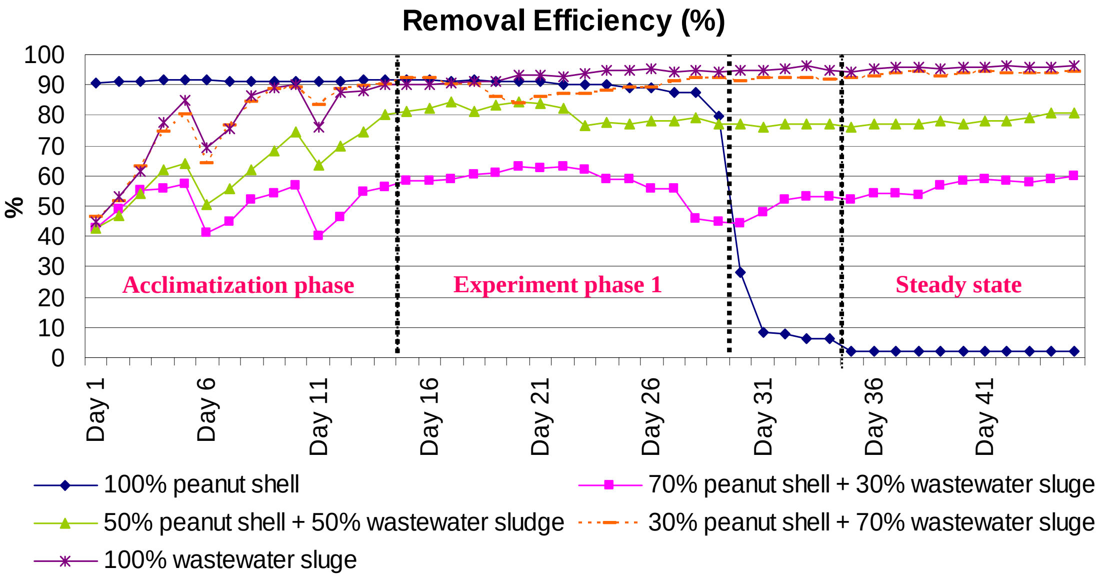


Figure 16 Removal efficiency of each experiment

Reactor with 70% peanut shell and 50% peanut shell has dropped in day 28 and 23 respectively, before recovered to the original level.

At steady stage, day 35 to day 45, the removal efficiency of the reactor with 100% peanut shell, 70% peanut shell + 30% wastewater sludge and 100% wastewater sludge was rather constant. As same as other phase, the removal efficiency of each reactor increased with the percentage of wastewater sludge in biofilter.

To compare the result from each experiment, t-test paired data comparison is selected to explain. The tabulated at 95% confidence level for 29 degree of freedom is 2.045. From table 11, every biofilter gave not different in result; however only the reactor with 30% peanut shell + 70% wastewater sludge and 100% wastewater sludge can reach over 90% of removal efficiency in the steady stage.

Relationship between inlet concentration, outlet concentration and efficiency of each reactor is shown in figure 17

Table 11 Paired data comparison

Compared reactors	T_0
0% sludge and 30% sludge	-0.051
0% sludge and 50% sludge	-0.151
0% sludge and 70% sludge	-0.188
0% sludge and 100% sludge	-0.206
30% sludge and 50% sludge	-0.993
30% sludge and 70% sludge	-0.917
30% sludge and 100% sludge	-1.161
50% sludge and 70% sludge	-0.459
50% sludge and 100% sludge	-0.693
70% sludge and 100% sludge	-0.263

From figure 17 , The reactor with peanut shell 100% could reduce the outlet concentration about 91%. However after the day 29, the efficiency decreased to less than 10% because the breakthrough had occurred in the filter bed in day 30 .

The reactor with peanut shell 70% and wastewater sludge 30% started with the efficiency 43% and developed to 58% in the acclimatization period. When the concentration of the inlet stream was increased, the removal efficiency decreased a little bit but it could recovered to almost the same level later. The experiment phase started with the removal efficiency 58.29%. However, at the day 28 the removal efficiency dropped off to 46% and increased again to 60% at the end of the experiment.

The reactor with peanut shell 50% and wastewater sludge 50%, had the efficiency from 43 to 81% in acclimatization period. Although the efficiency dropped when the inlet concentration was increased, it could develop in later days. The first 7 days in the experiment phase, it had average removal efficiency 83% and at the day 8 the efficiency decline to 76%. However it could restored to 81% at the end of the experiment.

For the biofilter with peanut 30% and wastewater sludge 70%, the behavior of the biofilter is similar to the reactor with 70% peanut shell + 30% wastewater sludge and 50% peanut shell + 50% wastewater sludge. The acclimatization phase had removal efficiency in the range of 43 - 91%. At the first 4 days of the experiment phase the average efficiency was about 89% and reduced a little bit to 84% in the 5th day. Then it could improve to 94% at the end of the experiment.

The reactor with 100% wastewater sludge started with the removal efficiency 44 – 90% in the acclimatization phase. And the efficiency increased to 96% at the end of the experiment without any efficiency decrease period occurred in the filter.

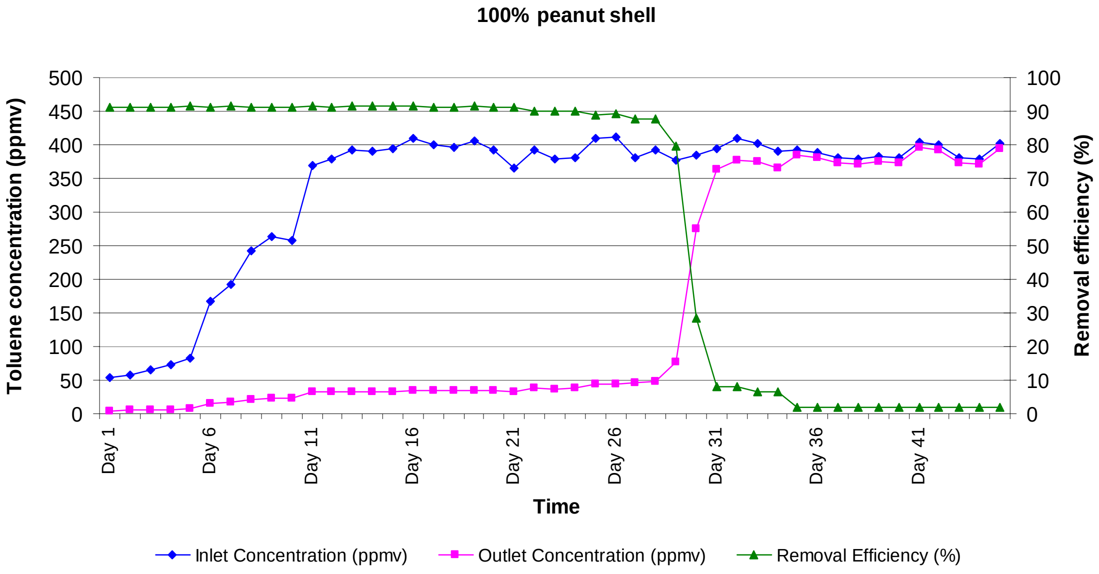
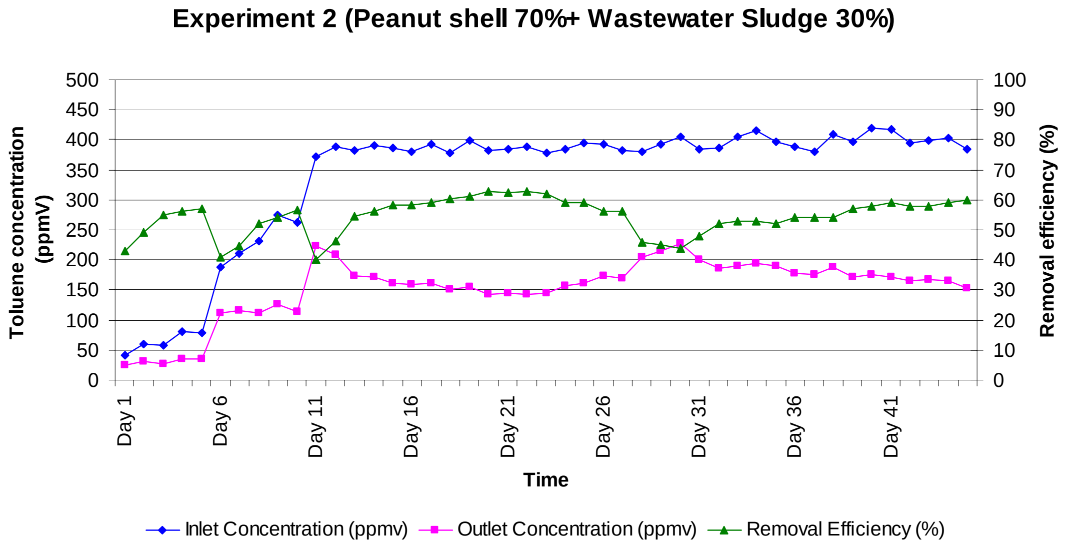
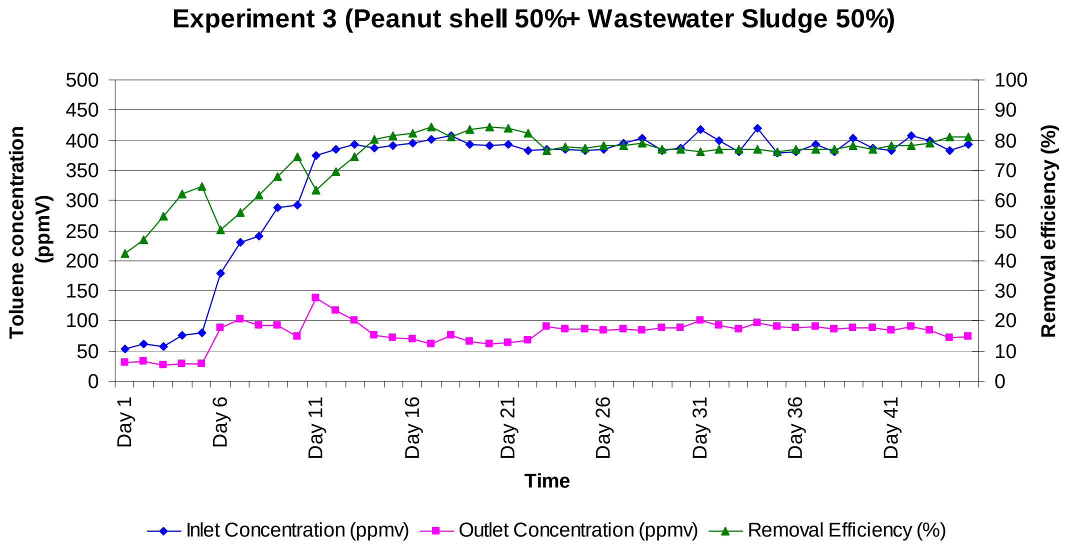


Figure 17 Inlet concentration, outlet concentration and removal efficiency

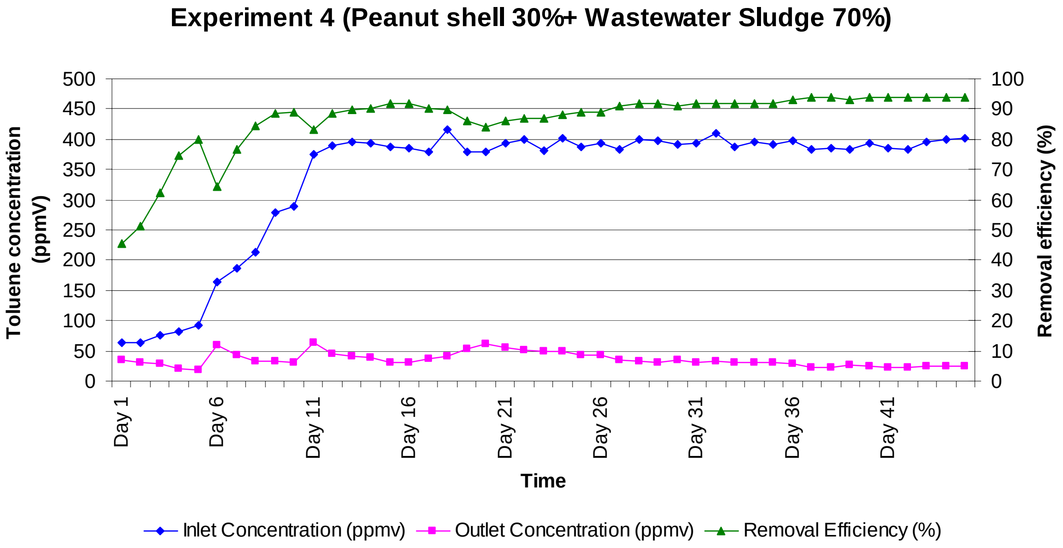


Experiment 2 (Peanut shell 70%+ Wastewater Sludge 30%)



Experiment 3 (Peanut shell 50%+ Wastewater Sludge 50%)

Figure 17 (Continued)



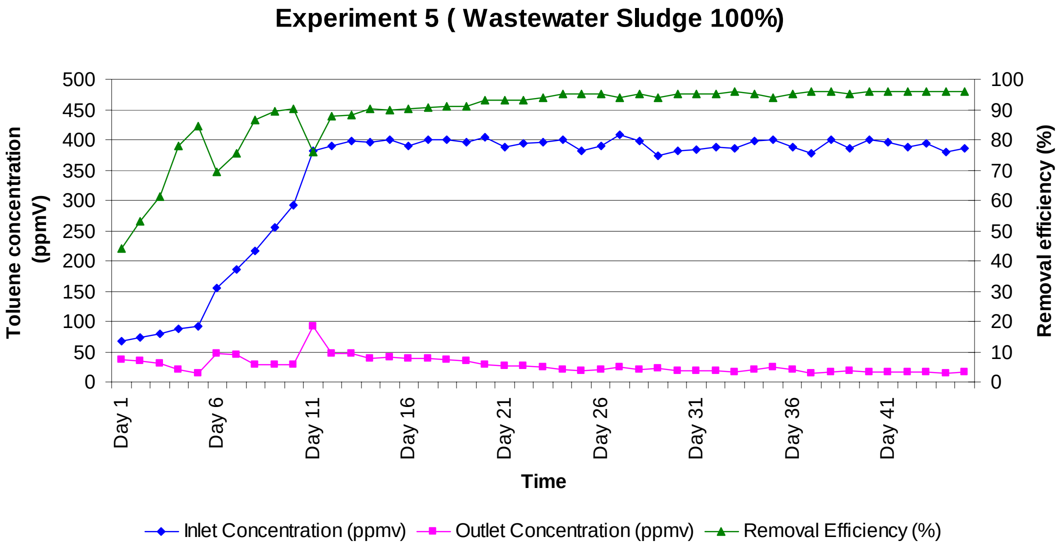


Figure 17 (Continued)

2.2 The elimination capacity

Elimination capacity of each biofilter is shown in figure 18

The elimination capacity is express how much of the contaminated air loading can be treated in the biofilter. The elimination capacity of each experiment is increase with the increasing of the inlet load to the biofilter even it decrease a little bit in the first day of the load increasing. The elimination capacity of the reactor with peanut shell 100% decreased with the lowering of the removal efficiency. Nevertheless, other reactors could extend the elimination capacity in almost the same level until the end of the experiment.

Elimination capacity performed similar to removal efficiency. The elimination capacity of the reactor with 100% peanut shell, 70% peanut shell and 30% wastewater sludge and the one with 100% wastewater sludge were almost constant in the steady stage and also increased with the percent of wastewater sludge in the biofilter.

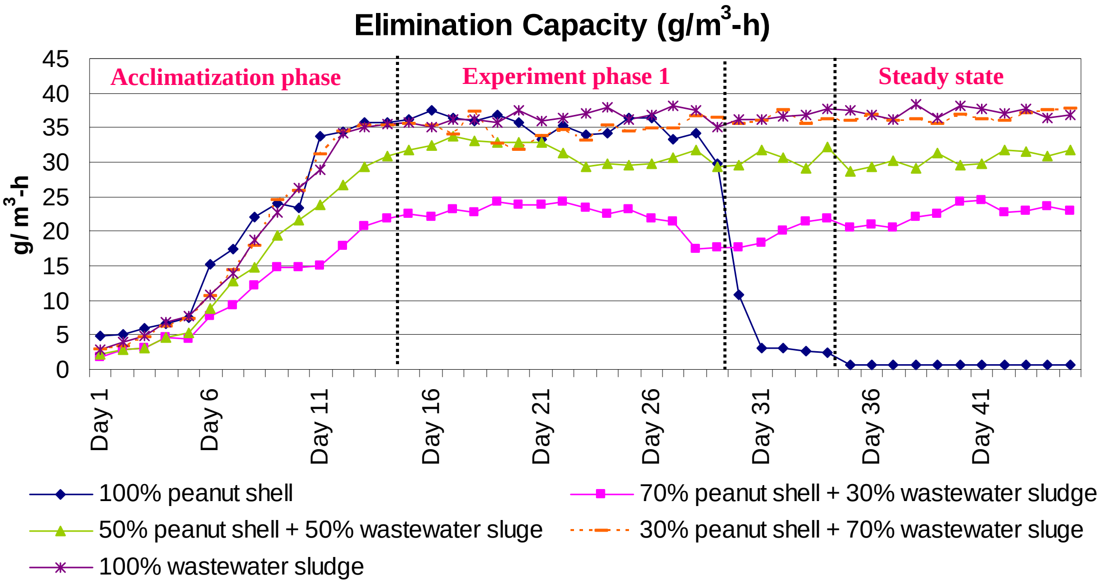


Figure 18 Elimination capacity

3. Study the mechanism in biofilter

3.1 Carbon dioxide (CO_2) generated

To determine the mechanism in biofilter, CO_2 generation is used as the indicator. CO_2 is generated from metabolism of the microorganisms. The result is shown in table 12.

Table 12 Carbon Dioxide generated from the experiment.

CO_2 Generated (g)	**Ratio of peanut shell : wastewater sludge**				
	100:0	**70:30**	**50:50**	**30:70**	**0:100**
Pre-experiment phase **Average** **Day 1 - Day 5**	0.03	0.40	0.58	0.70	0.73
SD **Day 1 - Day 15**	0.01	0.27	0.41	0.49	0.50
Experiment Phase **Average** **Day 16 - Day 29**	0.04	0.84	1.32	1.42	1.60
SD **Day 16 - Day 29**	0.01	0.01	0.10	0.13	0.11
Average **Day 35 - Day 45**	0.04	1.01	1.50	1.81	1.85
SD **Day 35 - Day 45**	0.01	0.04	0.04	0.05	0.04

From the stoichiometry in equation 26, toluene 1 mol or 92 grams will produce carbon dioxide 7 mol or 308 grams from oxidation. The ratio of CO_2 to toluene = 3.34

$$C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O \qquad (26)$$

When compare the total mass of toluene removed in the reactors each day with total CO_2 generated in table 13, the result show that the ratio of CO_2 generated to the toluene removed is less than the theoretical value, 3.34. It is believed that some of the carbon is incorporated into biomass.

Where

Toluene removed = Mass of toluene entering the filter × Removal Efficiency (27)

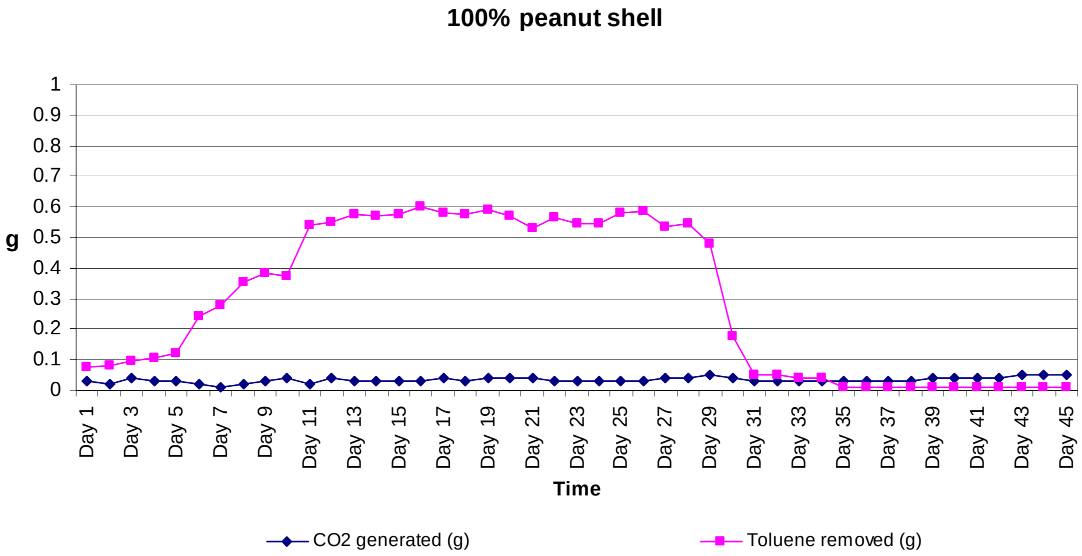
The average ratio of carbon dioxide generated to toluene removed of each experiment in the steady state is 3.27, 2.81, 3.08, 3.10 and 3.11 respectively. Figure 19.1 show the CO_2 generated and ratio of CO_2 generated to toluene elimination of each experiment.

The amount of CO_2 generated is increase with the percent of wastewater sludge in the biofilter as same as the ratio of CO_2 generated per toluene removal.

Table 13 Ratio of Carbon Dioxide generated to toluene removed

CO_2 generated/Toluene removed (g/g)	**Ratio of peanut shell : wastewater sludge**				
	100:0	**70:30**	**50:50**	**30:70**	**0:100**
Pre-experiment phase					
Average Day 1 - Day 5	0.15	2.08	2.27	2.20	2.31
SD Day 1 - Day 15	0.13	0.21	0.12	0.12	0.13
Experiment Phase					
Average Day 16 - Day 29	0.06	2.38	2.64	2.56	2.74
SD Day 16 - Day 29	0.02	0.29	0.31	0.19	0.17
Average Day 35 - Day 45	3.27	2.81	3.08	3.10	3.11
SD Day 35 - Day 45	0.74	0.11	0.07	0.08	0.07

However the CO_2 generated in reactor with 100% peanut shell was not related to the mass of toluene removed besides amount of CO_2 generated was much less than other experiment because there was no or very little microbial activities in this biofilter. Only adsorption occurred in this reactor.



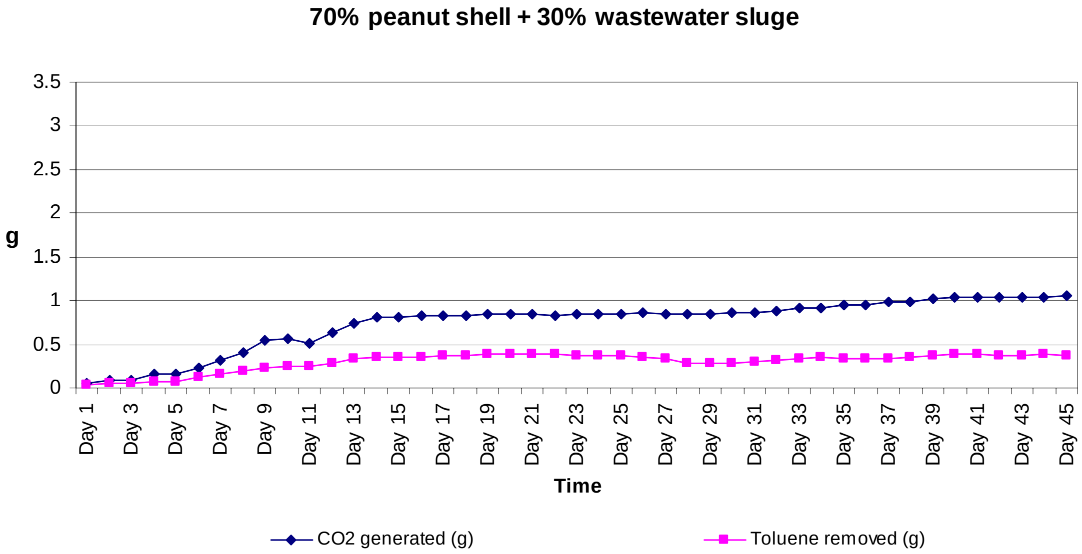
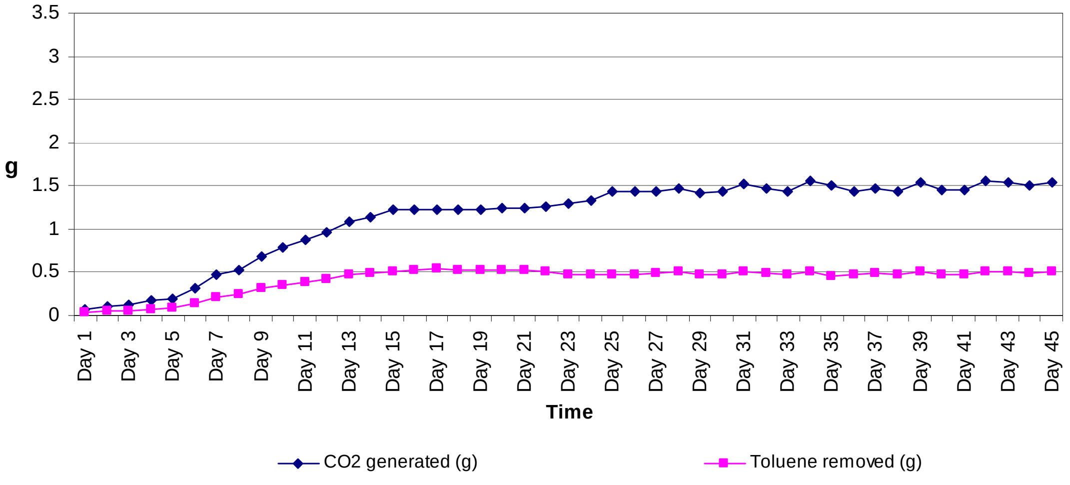
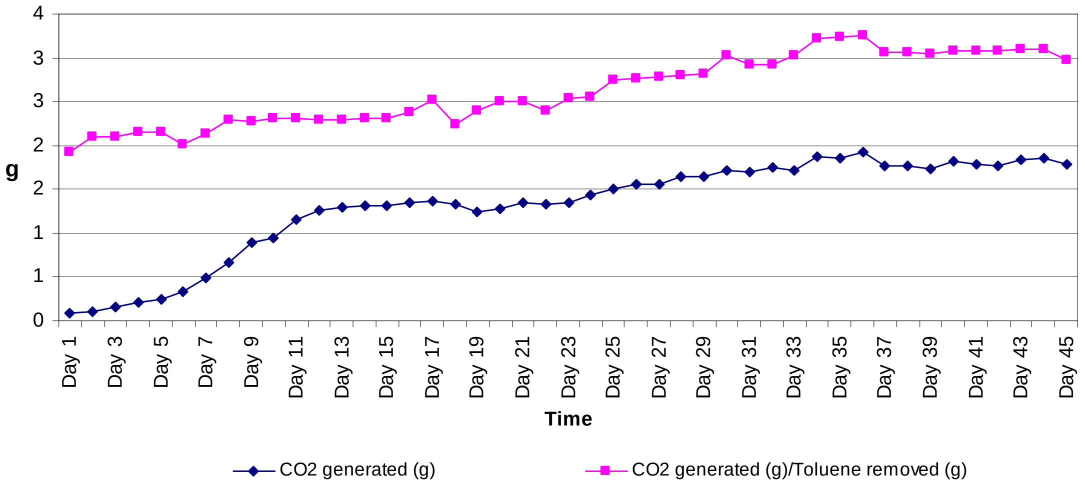


Figure 19 CO_2 generated and ratio of CO_2 generated to toluene elimination



50% peanut shell + 50% wastewater sluge



30% peanut shell + 70% wastewater sluge

Figure 19 (Continued)

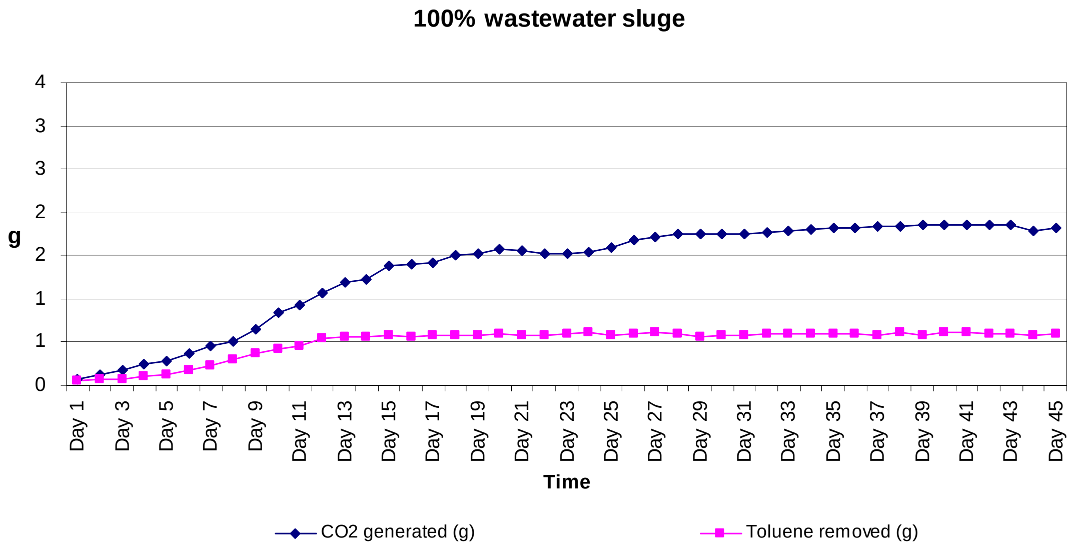


Figure 19 (Continued)

3.2 Weight of the mixture

Weight of the mixture was used to determine if the new cell was synthesized during the experiment. The result of weight measurement was shown in table 14. It was found that the dry weight of 100% peanut shell had no change when compare between before and after experiment whereas other reactors had dry weight increasing. The reactor with 30% peanut shell + 70% wastewater sludge and 100% wastewater sludge had the most increasing weight, 14 grams. The weight was gained from the weight of the new cell of microbial. The wet weight of all reactors increased because the microbial activities produced not only CO_2 but also water. Moreover the moist air entering the biofilter was another reason causes higher moisture content in the mixture by some water still remained in the reactors.

3.3 Compaction of packing material

The biofilter has been operated for 45 days, during that period the microbial populations would grow from the energy derived from the transformation of the pollutant and part of the carbon was incorporated into biomass. The synthesis of

Table 14 Weight of mixture measurement

Mixture	Dry weight gained (g)	Wet weight gained (g)	Moisture content increased (%)
Peanut 100%	0	2	0.7
Peanut 70% + Wastewater sludge 30%	12	34	3.5
Peanut 50% + Wastewater sludge 50%	12	41	3.7
Peanut 30% + Wastewater sludge 70%	14	53	4.0
Wastewater sludge 100 %	14	64	4.2

biomass caused the accumulation of microbial mass over time, which accounted into a change in reduction in void space, and compaction of the packing materials. The compaction the packing material was used to confirm the result of microbial activities and also guided for the most appropriate portion of the bed mixture selection.

The compaction of the packing material was measured once a week during experiment phase by measuring the distance from the original level to the top level of the mixture bed each time. The result is given in table 15.

From the result in table 15, reactor with 100% wastewater sludge had the most compaction and caused the difficulty of air flow through the bed because the bed was packed denser that other reactors. While reactor with 30% peanut shell and 100% wastewater sludge had the compaction less than the 100% wastewater slugged because shredded peanut shell could perform as the bulking agent for the bed.

Table 15 Compaction of the material

Bed destruction (cm)	Experiment				
	1	2	3	4	5
Week 1	0.00	0.00	0.00	0.00	0.20
Week 2	0.00	0.00	0.00	0.10	0.80
Week 3	0.00	0.05	0.20	0.90	3.50
Week 4	0.00	0.10	0.30	1.50	7.00

Discussion

1. Efficiency of the biofilter

The removal efficiency of the reactor with 100% peanut shell was almost constant during the acclimatization state (Day 1 - 15) until day 29. Increasing the concentration of toluene to this reactor did not lowering the removal efficiency. However the breakthrough took place at day 30. After the breakthrough, the removal efficiency fell to almost zero. While other reactor had similar behavior, the removal efficiency reduced when the concentration of inlet steam increased and they can recover the removal efficiency to nearly the initial after that. During the experiment state (day 16 – 45), reactor with 70% peanut shell + 30% wastewater sludge and 50% peanut shell + 50% wastewater sludge had a little descend in the removal efficiency. Possibly because the peanut shell in the mixture has reached the adsorption capacity. However, overall efficiency of each experiment can prolong through the end of the experiment. The removal efficiency of the reactor contained wastewater sludge was not change very much because the microorganisms in the wastewater sludge can maintain the system in the steady state when there was no change in the load of inlet steam.

When compare the efficiency of each reactor in the steady state, reactor with 100% wastewater sludge had the highest removal efficiency and the removal efficiency of each reactor enhance with the increasing of the ratio of the wastewater sludge in the biofilter.

2. Mechanism in biofilter

There were 2 mechanisms founded from this study. First, the adsorption on the peanut shell and the second was biodegradation by the microorganism in wastewater sludge. Because in the experiment which no wastewater sludge, only the peanut shells could hold the removal efficiency at about 90% for 29 days and after that the efficiency drop to almost zero. While other reactors, the microorganism in wastewater sludge could degrade the toluene in to carbon dioxide and the efficiency of the system can maintain until the end of the experiment along 45 days although during the experiment there was some period that the efficiency decreased because the adsorption on peanut shell had breakthrough.

When consider the ratio of CO_2 generated to the mass of toluene removed (g/g), it is found that the experiment 1 which contains 100% peanut shell generated CO_2 very low when compare which toluene removed and did not go along with the mass of toluene removed. It can conclude that the removal of toluene in this column was not arising from the microbial activities. Other reactor had the relation between the CO_2 generated to the toluene removed in the same direction. This ratio is higher along with the percentage of wastewater in each reactor. However, the ratio of CO_2 generated per toluene removed from all reactors contained wastewater sludge were less than theoretical value, 3.34 g CO_2/ g toluene, because some of the carbon was used for the new cells synthetic and it was proved by the dry weight gained after the experiment.

CONCLUSION AND RECOMMENDATIONS

Conclusion

The removal efficiency and the elimination capacity of the biofilter is depends on the volume of the wastewater sludge in the reactor. The reactor with 30% 50% 70% and 100% wastewater used to eliminate toluene contaminated air stream had their average removal efficiency during the steady stage 57, 79, 94 and 96 % respectively. When compare the elimination capacity of these reactors, the average elimination capacity of each reactor in the steady state, day 35 – day 45, was 22.52, 30.35, 36.51 and 37.19 g/m^{3}h respectively. The result show that the reactor with 70% and 100% wastewater sludge had not too different in both removal efficiency and elimination capacity. However, the reactor with 70% wastewaters sludge had smaller bed compaction; therefore the contaminated air would flow through the bed easier.

From the result of the experiment it can conclude that the biofilter can reduce the concentration of toluene from air stream by 2 mechanisms, adsorption on the peanut shell and biodegradation. However, the biofilter with peanut shell 100% cannot prolong the removal efficiency because the breakthrough was occurred when its reached its capacity while the biodegradation in other experiment can continuously perform in the biofilter until the end of the experiment.

However, this study select the EBRT 133 seconds which quite a large number when compare with typical ERTB 15 – 60 seconds as shown in table 7. If apply this biofilter in the field work, it will required a large reactor. Therefore, this biofilter is appropriate to apply with the low flow rate contaminated air stream.

Recommendations

This study should extend and further study about following issues

1. Determine the maximum elimination capacity of each proportion of the media by varies inlet loading to the reactor.
2. Various type of VOCs as well as the mixtures VOCs to indicate the performance of the biofilter compare with the various VOCs.
3. Various type of material for the biofilter media.

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APPENDICES

Appendix A

The reading concentration of inlet and outlet toluene

Appendix Table A1 Inlet and outlet concentration of reactor with 100% Peanut shell

Day	Inlet				Outlet			
	Replication			Average	Replication			Average
	1	2	3		1	2	3	
Day 1	105	101	106	103.9	9.5	10	8	9.1
Day 2	109	115	111	111.8	9	10	11	9.9
Day 3	128	130	130	129.4	12	10	13	11.5
Day 4	140	145	144	143.1	13	12.5	13	12.7
Day 5	160	162	160	160.8	15	11	14	13.3
Day 6	325	330	327	327.5	30	27	28	28.4
Day 7	379	373	377	376.5	32	35	31	32.5
Day 8	475	472	477	474.5	39	42	42	41.1
Day 9	515	514	518	515.7	49	44	43	45.2
Day 10	504	505	503	503.9	48	42	43	44.3
Day 11	725	720	726	723.5	65	61	61	62.2
Day 12	744	739	741	741.2	62	68	65	64.9
Day 13	770	765	771	768.6	65	64	64	64.2
Day 14	769	764	767	766.7	69	62	64	64.9
Day 15	778	773	773	774.5	62	69	64	65.1
Day 16	802	803	807	803.9	68	72	65	68.2
Day 17	786	784	783	784.3	71	66	70	68.9
Day 18	779	774	776	776.5	67	69	66	67.2
Day 19	793	798	791	794.1	66	71	67	68.1
Day 20	772	773	767	770.6	65	69	67	66.9
Day 21	715	718	720	717.6	60	66	63	62.9
Day 22	772	772	768	770.6	79	73	78	76.8
Day 23	741	744	744	743.1	70	75	75	73.3
Day 24	747	746	742	745.1	76	77	70	74.3
Day 25	799	802	805	802.0	86	89	90	88.2

Appendix Table A1 (Continued)

Day	Inlet				Outlet			
	Replication			Average	Replication			Average
	1	2	3		1	2	3	
Day 26	803	808	807	805.9	87	88	89	87.8
Day 27	748	744	749	747.1	90	92	92	91.3
Day 28	769	765	772	768.6	92	99	95	95.2
Day 29	738	739	741	739.2	154	152	149	151.5
Day 30	754	753	758	754.9	541	544	537	540.5
Day 31	775	772	777	774.5	715	707	716	712.5
Day 32	800	806	800	802.0	735	740	741	738.7
Day 33	783	788	788	786.3	740	732	732	734.5
Day 34	764	766	770	766.7	720	716	714	716.8
Day 35	769	765	772	768.6	752	759	749	753.5
Day 36	762	761	759	760.8	741	750	746	745.7
Day 37	744	748	749	747.1	735	731	731	732.5
Day 38	739	742	743	741.2	729	726	725	726.6
Day 39	749	752	746	749.0	733	735	735	734.5
Day 40	746	748	741	745.1	730	729	733	730.7
Day 41	792	792	787	790.2	771	775	779	774.9
Day 42	785	781	787	784.3	768	766	774	769.3
Day 43	746	748	747	747.1	729	736	733	732.8
Day 44	741	744	744	743.1	725	730	732	729.0
Day 45	782	789	788	786.3	775	772	767	771.3

Appendix Table A2 Inlet and outlet concentration of reactor with 70% peanut shell + 30% wastewater sludge

Day	**Inlet**				**Outlet**			
	Replication			**Average**	**Replication**			**Average**
	1	**2**	**3**		**1**	**2**	**3**	
Day 1	85	84	78	82.4	47	49	45	46.9
Day 2	120	111	116	115.7	60	62	55	59.0
Day 3	115	115	111	113.7	50	55	49	51.2
Day 4	154	159	163	158.8	65	71	74	69.9
Day 5	160	154	154	155.9	67	69	65	67.0
Day 6	375	367	370	370.6	220	215	221	218.6
Day 7	410	415	410	411.8	225	230	228	227.8
Day 8	459	452	454	454.9	215	220	217	217.4
Day 9	537	533	542	537.3	245	244	252	247.1
Day 10	511	518	518	515.7	229	220	222	223.7
Day 11	735	727	726	729.4	438	433	437	436.0
Day 12	761	763	758	760.8	405	411	408	408.2
Day 13	752	748	747	749.0	340	342	342	341.4
Day 14	760	766	768	764.7	336	339	332	335.6
Day 15	755	757	759	756.9	315	316	313	314.6
Day 16	740	746	749	745.1	311	315	306	310.8
Day 17	765	769	772	768.6	310	315	320	315.0
Day 18	742	740	742	741.2	296	294	295	295.0
Day 19	785	780	782	782.4	303	309	301	304.2
Day 20	744	752	751	749.0	275	279	283	278.9
Day 21	755	751	753	752.9	282	285	281	282.5
Day 22	762	761	759	760.8	285	277	282	281.4
Day 23	746	744	739	743.1	286	279	282	282.4
Day 24	750	755	754	752.9	310	306	310	308.7
Day 25	775	770	773	772.5	319	320	311	316.7

Appendix Table A2 (Continued)

Day	Inlet				Outlet			
	Replication			Average	Replication			Average
	1	2	3		1	2	3	
Day 26	769	775	768	770.6	335	340	342	339.1
Day 27	751	754	748	751.0	329	334	328	330.4
Day 28	744	741	750	745.1	403	400	404	402.4
Day 29	765	769	772	768.6	425	422	421	422.7
Day 30	795	792	789	792.2	444	448	439	443.6
Day 31	751	754	754	752.9	390	395	390	391.5
Day 32	759	755	757	756.9	364	366	360	363.3
Day 33	799	793	790	794.1	372	375	373	373.2
Day 34	815	810	816	813.7	380	388	379	382.5
Day 35	775	779	781	778.4	375	371	375	373.6
Day 36	761	760	761	760.8	349	350	351	350.0
Day 37	741	750	744	745.1	344	341	343	342.7
Day 38	805	800	807	803.9	366	370	373	369.8
Day 39	775	777	783	778.4	330	339	335	334.7
Day 40	823	825	823	823.5	349	345	344	345.9
Day 41	820	818	821	819.6	335	333	340	336.0
Day 42	771	769	778	772.5	326	322	325	324.5
Day 43	779	783	779	780.4	329	330	324	327.8
Day 44	790	791	790	790.2	320	324	328	324.0
Day 45	755	751	753	752.9	303	300	301	301.2

Appendix Table A3 Inlet and outlet concentration of reactor with 50% peanut shell + 50% wastewater sludge

Day	**Inlet**				**Outlet**			
	Replication			**Average**	**Replication**			**Average**
	1	**2**	**3**		**1**	**2**	**3**	
Day 1	109	101	108	105.9	65	60	57	60.8
Day 2	120	125	120	121.6	62	69	63	64.6
Day 3	111	112	112	111.8	49	52	50	50.5
Day 4	146	148	153	149.0	59	55	54	56.2
Day 5	155	159	162	158.8	60	58	51	56.5
Day 6	345	349	353	349.0	178	170	172	173.5
Day 7	455	451	453	452.9	205	200	196	200.3
Day 8	470	477	471	472.5	179	185	176	180.1
Day 9	564	561	569	564.7	180	183	180	181.0
Day 10	570	577	571	572.5	149	142	147	145.9
Day 11	739	733	734	735.3	270	265	272	269.0
Day 12	755	754	756	754.9	230	232	228	229.9
Day 13	770	771	777	772.5	195	198	201	197.9
Day 14	759	758	754	756.9	152	149	143	148.1
Day 15	762	769	769	766.7	140	146	141	142.2
Day 16	775	771	778	774.5	139	131	140	136.7
Day 17	783	789	793	788.2	120	125	123	122.6
Day 18	803	800	797	800.0	150	155	148	151.1
Day 19	776	771	771	772.5	125	129	130	127.9
Day 20	764	765	771	766.7	119	120	124	121.1
Day 21	771	775	766	770.6	120	128	121	123.1
Day 22	749	747	751	749.0	130	132	132	131.5
Day 23	760	752	753	754.9	178	182	174	178.0
Day 24	750	755	754	752.9	168	171	163	167.5
Day 25	751	750	752	751.0	169	171	174	171.3

Appendix Table A3 (Continued)

Day	Inlet				Outlet			
	Replication			Average	Replication			Average
	1	2	3		1	2	3	
Day 26	755	749	755	752.9	161	169	167	165.6
Day 27	770	777	777	774.5	172	171	168	170.4
Day 28	791	790	790	790.2	161	168	169	165.9
Day 29	749	745	753	749.0	170	175	172	172.3
Day 30	755	759	757	756.9	175	172	175	174.1
Day 31	820	822	817	819.6	192	199	199	196.7
Day 32	788	780	779	782.4	180	177	183	179.9
Day 33	741	744	750	745.1	166	175	173	171.4
Day 34	819	826	820	821.6	186	189	192	189.0
Day 35	744	741	744	743.1	177	179	179	178.4
Day 36	742	750	749	747.1	170	175	170	171.8
Day 37	775	770	773	772.5	175	178	180	177.7
Day 38	746	740	749	745.1	173	175	166	171.4
Day 39	790	791	795	792.2	172	174	177	174.3
Day 40	755	759	757	756.9	172	174	176	174.1
Day 41	749	750	748	749.0	165	160	169	164.8
Day 42	795	803	802	800.0	174	175	179	176.0
Day 43	786	788	779	784.3	161	165	168	164.7
Day 44	745	750	752	749.0	140	142	145	142.3
Day 45	771	770	771	770.6	150	148	141	146.4

Appendix Table A4 Inlet and outlet concentration of reactor with 30% peanut shell + 70% wastewater sludge

Day	**Inlet**				**Outlet**			
	Replication			**Average**	**Replication**			**Average**
	1	**2**	**3**		**1**	**2**	**3**	
Day 1	120	125	126	123.7	65	69	68	67.4
Day 2	121	130	127	125.9	60	62	63	61.5
Day 3	148	145	151	147.8	50	59	58	55.5
Day 4	159	162	163	161.4	44	43	37	41.2
Day 5	175	179	182	178.8	35	38	35	35.9
Day 6	320	327	319	322.2	119	114	112	114.9
Day 7	362	369	371	367.5	82	85	90	85.8
Day 8	420	421	415	418.8	61	67	69	65.6
Day 9	544	543	548	544.9	60	65	65	63.5
Day 10	563	569	572	567.8	61	66	59	61.8
Day 11	733	735	741	736.5	121	125	125	123.7
Day 12	760	765	769	764.5	85	88	94	89.1
Day 13	771	775	775	773.5	78	82	80	80.1
Day 14	770	773	771	771.2	75	79	75	76.2
Day 15	761	759	763	761.0	60	65	59	61.5
Day 16	750	758	757	754.9	61	62	58	60.4
Day 17	740	742	747	743.1	75	77	71	74.3
Day 18	817	815	809	813.7	80	85	81	81.9
Day 19	741	744	750	745.1	101	103	109	104.3
Day 20	746	742	747	745.1	120	118	120	119.2
Day 21	772	770	776	772.5	105	111	108	108.2
Day 22	782	782	783	782.4	100	105	100	101.7
Day 23	745	744	752	747.1	95	99	97	97.1
Day 24	789	785	791	788.2	92	98	94	94.6
Day 25	761	765	756	760.8	80	85	86	83.7

Appendix Table A4 (Continued)

Day	**Inlet**				**Outlet**			
	Replication			**Average**	**Replication**			**Average**
	1	**2**	**3**		**1**	**2**	**3**	
Day 26	773	775	770	772.5	85	80	90	85.0
Day 27	751	755	747	751.0	68	65	70	67.6
Day 28	782	788	783	784.3	60	64	64	62.7
Day 29	775	779	781	778.4	62	65	60	62.3
Day 30	765	767	774	768.6	65	72	71	69.2
Day 31	775	771	766	770.6	65	60	60	61.6
Day 32	800	802	804	802.0	66	62	64	64.2
Day 33	759	762	761	760.8	60	62	61	60.9
Day 34	770	775	779	774.5	60	62	64	62.0
Day 35	767	769	770	768.6	61	65	58	61.5
Day 36	779	777	779	778.4	55	53	55	54.5
Day 37	755	751	753	752.9	42	44	50	45.2
Day 38	759	759	753	756.9	45	49	42	45.4
Day 39	749	758	752	752.9	50	55	53	52.7
Day 40	775	771	772	772.5	46	48	45	46.4
Day 41	752	755	758	754.9	42	45	49	45.3
Day 42	753	751	749	751.0	46	48	41	45.1
Day 43	779	778	772	776.5	45	44	51	46.6
Day 44	782	780	785	782.4	48	49	44	46.9
Day 45	788	785	792	788.2	45	49	48	47.3

Appendix Table A5 Inlet and outlet concentration of reactor with 100% wastewater sludge

Day	**Inlet**				**Outlet**			
	Replication			**Average**	**Replication**			**Average**
	1	**2**	**3**		**1**	**2**	**3**	
Day 1	130	135	130	131.6	70	75	75	73.4
Day 2	145	144	149	146.0	69	65	71	68.3
Day 3	152	159	159	156.8	58	63	61	60.8
Day 4	172	177	171	173.4	35	38	43	38.5
Day 5	181	183	178	180.6	29	31	24	28.2
Day 6	305	300	306	303.7	91	93	96	93.5
Day 7	360	364	364	362.7	85	90	92	89.1
Day 8	430	423	421	424.7	55	59	56	56.5
Day 9	505	500	499	501.2	50	58	54	54.1
Day 10	571	573	568	570.6	55	58	56	56.4
Day 11	749	750	748	749.0	180	182	177	179.6
Day 12	761	768	762	763.7	90	92	98	93.5
Day 13	781	779	780	780.0	95	93	90	92.7
Day 14	770	775	780	774.9	75	79	78	77.4
Day 15	782	780	787	783.1	80	82	74	78.8
Day 16	760	765	769	764.7	78	75	73	75.5
Day 17	780	788	785	784.3	70	75	80	74.9
Day 18	781	785	781	782.4	70	75	66	70.4
Day 19	770	777	777	774.5	69	68	72	69.7
Day 20	790	793	793	792.2	52	58	56	55.5
Day 21	755	759	762	758.8	50	55	54	53.1
Day 22	771	772	769	770.6	58	52	52	53.9
Day 23	775	773	776	774.5	45	49	45	46.5
Day 24	785	790	784	786.3	36	38	44	39.3
Day 25	748	750	743	747.1	35	39	38	37.4

Appendix Table A5 (Continued)

Day	**Inlet**				**Outlet**			
	Replication			**Average**	**Replication**			**Average**
	1	**2**	**3**		**1**	**2**	**3**	
Day 26	762	760	766	762.7	35	39	40	38.1
Day 27	798	800	802	800.0	50	45	49	48.0
Day 28	775	779	781	778.4	38	39	40	38.9
Day 29	736	730	734	733.3	40	45	47	44.0
Day 30	745	749	747	747.1	35	39	38	37.4
Day 31	752	751	750	751.0	38	39	36	37.5
Day 32	759	758	759	758.8	37	35	42	37.9
Day 33	750	755	760	754.9	30	32	29	30.2
Day 34	782	781	778	780.4	39	38	40	39.0
Day 35	789	782	788	786.3	45	49	48	47.2
Day 36	761	762	759	760.8	35	38	41	38.0
Day 37	738	740	740	739.2	26	29	34	29.6
Day 38	783	784	786	784.3	30	35	29	31.4
Day 39	751	755	759	754.9	35	38	40	37.7
Day 40	785	780	782	782.4	30	35	29	31.3
Day 41	775	770	779	774.5	31	32	30	31.0
Day 42	759	755	762	758.8	32	30	29	30.4
Day 43	770	775	773	772.5	31	34	28	30.9
Day 44	749	744	742	745.1	32	31	26	29.8
Day 45	755	759	751	754.9	32	31	28	30.2

Appendix Table A6 Removal Efficiency of eachreactor

Removal Efficiency (%)	**Ratio of peanut shell : wastewater sludge**				
	100 : 0	**70 : 30**	**50 : 50**	**30 : 70**	**0 :100**
Day 1	91.21	43.00	42.56	45.53	44.23
Day 2	91.12	49.00	46.90	51.12	53.19
Day 3	91.11	55.00	54.86	62.44	61.23
Day 4	91.13	56.00	62.32	74.44	77.79
Day 5	91.72	57.00	64.43	79.91	84.41
Day 6	91.32	41.01	50.30	64.32	69.23
Day 7	91.36	44.67	55.77	76.66	75.45
Day 8	91.33	52.21	61.89	84.34	86.69
Day 9	91.23	54.00	67.94	88.35	89.21
Day 10	91.21	56.62	74.52	89.11	90.11
Day 11	91.40	40.23	63.41	83.20	76.02
Day 12	91.25	46.35	69.55	88.34	87.76
Day 13	91.65	54.42	74.38	89.65	88.12
Day 14	91.54	56.11	80.43	90.12	90.01
Day 15	91.59	58.43	81.45	91.92	89.94
Day 16	91.52	58.29	82.35	92.00	90.13
Day 17	91.21	59.02	84.44	90.00	90.45
Day 18	91.34	60.20	81.11	89.94	91.00
Day 19	91.43	61.12	83.45	86.00	91.00
Day 20	91.32	62.77	84.21	84.00	93.00
Day 21	91.23	62.48	84.02	86.00	93.00
Day 22	90.03	63.01	82.45	87.00	93.00
Day 23	90.13	62.00	76.42	87.00	94.00
Day 24	90.03	59.00	77.76	88.00	95.00
Day 25	89.00	59.00	77.19	89.00	95.00
Day 26	89.10	56.00	78.00	89.00	95.00
Day 27	87.78	56.00	78.00	91.00	94.00

Appendix Table A6 (Continued)

Removal Efficiency	Ratio of peanut shell : wastewater sludge				
(%)	**100 : 0**	**70 : 30**	**50 : 50**	**30 : 70**	**0 :100**
Day 28	87.61	46.00	79.00	92.00	95.00
Day 29	79.50	45.00	77.00	92.00	94.00
Day 30	28.40	44.00	77.00	91.00	95.00
Day 31	8.00	48.00	76.00	92.00	95.00
Day 32	7.89	52.00	77.00	92.00	95.00
Day 33	6.58	53.00	77.00	92.00	96.00
Day 34	6.51	53.00	77.00	92.00	95.00
Day 35	1.97	52.00	76.00	92.00	94.00
Day 36	1.98	54.00	77.00	93.00	95.00
Day 37	1.95	54.00	77.00	94.00	96.00
Day 38	1.96	54.00	77.00	94.00	96.00
Day 39	1.94	57.00	78.00	93.00	95.00
Day 40	1.93	58.00	77.00	94.00	96.00
Day 41	1.93	59.00	78.00	94.00	96.00
Day 42	1.92	58.00	78.00	94.00	96.00
Day 43	1.91	58.00	79.00	94.00	96.00
Day 44	1.90	59.00	81.00	94.00	96.00
Day 45	1.91	60.00	81.00	94.00	96.00
Average Acclimatization phase	91.31	50.98	63.32	77.43	77.57
SD Acclimatization phase	0.32	6.29	11.75	14.71	14.56
Average Day 16 – Day 29	89.37	57.85	80.38	88.77	93.13
SD Day 16 - Day 29	3.13	5.71	3.01	2.55	1.80
Average Steady stage phase	1.92	56.64	78.05	93.63	95.67
SD Steady stage phase	0.09	2.69	1.62	0.66	0.67

Appendix Table A7 Elimination capacity of each experiment

Elimination capacity (g/m^3-h)	Ratio of peanut shell : wastewater sludge				
	100 : 0	**70 : 30**	**50 : 50**	**30 : 70**	**0 :100**
Day 1	4.82	1.80	2.29	2.87	2.96
Day 2	5.18	2.88	2.90	3.27	3.95
Day 3	6.00	3.18	3.12	4.70	4.88
Day 4	6.64	4.53	4.73	6.11	6.86
Day 5	7.50	4.52	5.21	7.27	7.76
Day 6	15.22	7.73	8.93	10.54	10.70
Day 7	17.50	9.36	12.85	14.33	13.93
Day 8	22.05	12.09	14.88	17.97	18.73
Day 9	23.94	14.76	19.52	24.50	22.75
Day 10	23.39	14.86	21.71	25.75	26.16
Day 11	33.65	14.93	23.72	31.18	28.97
Day 12	34.41	17.94	26.72	34.37	34.10
Day 13	35.84	20.74	29.24	35.29	34.97
Day 14	35.71	21.83	30.98	35.36	35.49
Day 15	36.10	22.50	31.77	35.59	35.84
Day 16	37.44	22.10	32.45	35.34	35.07
Day 17	36.37	23.05	33.84	34.00	36.07
Day 18	36.06	22.68	32.99	37.21	36.20
Day 19	36.91	24.30	32.78	32.58	35.83
Day 20	35.78	23.90	32.82	31.82	37.46
Day 21	33.29	23.91	32.92	33.78	35.88
Day 22	35.27	24.36	31.40	34.60	36.44
Day 23	34.05	23.42	29.33	33.04	37.02
Day 24	34.11	22.58	29.76	35.27	37.98
Day 25	36.29	23.16	29.47	34.42	36.08
Day 26	36.51	21.93	29.86	34.96	36.84
Day 27	33.34	21.37	30.71	34.75	38.23

Appendix Table A7 (Continued)

Elimination capacity (g/m^3-h)	Ratio of peanut shell : wastewater sludge				
	100 : 0	**70 : 30**	**50 : 50**	**30 : 70**	**0 :100**
Day 28	34.24	17.41	31.73	36.69	37.60
Day 29	29.88	17.57	29.32	36.41	35.05
Day 30	10.88	17.71	29.63	35.56	36.08
Day 31	3.12	18.36	31.66	36.04	36.27
Day 32	3.19	20.00	30.62	37.51	36.65
Day 33	2.60	21.39	29.17	35.59	36.85
Day 34	2.51	21.91	32.16	36.23	37.69
Day 35	0.74	20.57	28.71	35.95	37.58
Day 36	0.74	20.88	29.24	36.81	36.75
Day 37	0.71	20.45	30.24	35.99	36.08
Day 38	0.71	22.06	29.17	36.17	38.28
Day 39	0.71	22.55	31.41	35.60	36.46
Day 40	0.70	24.27	29.63	36.92	38.19
Day 41	0.75	24.57	29.70	36.08	37.80
Day 42	0.74	22.77	31.72	35.89	37.04
Day 43	0.70	23.00	31.50	37.11	37.71
Day 44	0.69	23.69	30.84	37.39	36.37
Day 45	0.69	22.96	31.73	37.67	36.85
Average Acclimatization phase	20.53	11.58	15.90	19.27	19.20
SD Acclimatization phase	12.50	7.28	11.01	13.03	12.69
Average Day 16 – Day 29	34.97	22.27	31.38	34.63	36.55
SD Day 16 - Day 29	1.99	2.21	1.61	1.54	1.00
Average Steady stage phase	0.72	22.52	30.35	36.51	37.19
SD Steady stage phase	0.02	1.42	1.13	0.70	0.76

Appendix B

Volume of H_2SO_4 used for titration

Appendix Table B1 Volume of H_2SO_4 used to titrate for CO_2 generated from reactor with 100% peanut shell

	Replication			**Average**
	1	**2**	**3**	
Day 1	49.4	49.4	49.2	49.30
Day 2	49.5	49.5	49.5	49.50
Day 3	49.2	49.1	49.1	49.10
Day 4	49.3	49.3	49.3	49.30
Day 5	49.4	49.2	49.3	49.30
Day 6	49.5	49.4	49.5	49.50
Day 7	49.7	49.9	49.9	49.80
Day 8	49.6	49.5	49.5	49.50
Day 9	49.3	49.4	49.3	49.30
Day 10	49.2	49.1	49.1	49.10
Day 11	49.6	49.5	49.4	49.50
Day 12	49.1	49.2	49	49.10
Day 13	49.3	49.3	49.4	49.30
Day 14	49.4	49.3	49.3	49.30
Day 15	49.3	49.4	49.3	49.30
Day 16	49.3	49.3	49.3	49.30
Day 17	49.1	49.1	49.1	49.10
Day 18	49.3	49.2	49.3	49.30
Day 19	49.1	49.1	49	49.10
Day 20	49.1	49.2	49.1	49.10
Day 21	49.1	49.1	49.1	49.10
Day 22	49.2	49.3	49.3	49.30
Day 23	49.3	49.3	49.2	49.30
Day 24	49.2	49.3	49.3	49.30
Day 25	49.3	49.2	49.4	49.30
Day 26	49.2	49.3	49.3	49.30

Appendix B1 (Continued)

	Replication			Average
	1	2	3	
Day 27	49.1	49.1	49.1	49.10
Day 28	49	49.1	49.1	49.10
Day 29	48.9	48.9	48.9	48.90
Day 30	49.1	49.1	49	49.10
Day 31	49.3	49.2	49.3	49.30
Day 32	49.3	49.2	49.3	49.30
Day 33	49.2	49.3	49.3	49.30
Day 34	49.3	49.3	49.4	49.30
Day 35	49.4	49.4	49.2	49.30
Day 36	49.3	49.2	49.3	49.30
Day 37	49.3	49.2	49.3	49.30
Day 38	49.3	49.3	49.3	49.30
Day 39	49.2	49.1	49.1	49.10
Day 40	49.1	49.1	49.1	49.10
Day 41	49.1	49.1	49.1	49.10
Day 42	49.1	49.2	49.1	49.10
Day 43	48.8	48.9	48.9	48.90
Day 44	48.9	48.9	48.8	48.90
Day 45	48.9	48.9	48.9	48.90

Appendix Table B2 Volume of H_2SO_4 used to titrate for CO_2 generated from reactor with 70% peanut shell + 30% wastewater sludge

	Replication			Average
	1	2	3	
Day 1	48.9	49	48.9	48.90
Day 2	48.2	48.2	48.2	48.20
Day 3	48	48.1	48	48.00
Day 4	46.6	46.5	46.6	46.60
Day 5	46.6	46.6	46.7	46.60
Day 6	44.8	44.7	44.9	44.80
Day 7	43	43	43	43.00
Day 8	40.5	40.8	40.7	40.70
Day 9	37.7	37.8	37.7	37.70
Day 10	37.3	37.3	37.4	37.30
Day 11	38.3	38.4	38.5	38.40
Day 12	35.5	35.5	35.4	35.50
Day 13	33.1	33.2	33.2	33.20
Day 14	31.8	31.8	31.7	31.80
Day 15	31.6	31.7	31.7	31.60
Day 16	31.5	31.4	31.4	31.40
Day 17	31.1	31.1	31.2	31.10
Day 18	31.1	31.1	31.1	31.10
Day 19	30.9	30.9	30.9	30.90
Day 20	30.9	30.9	30.9	30.90
Day 21	30.8	30.9	30.9	30.90
Day 22	31.1	30.9	31.1	31.10
Day 23	30.9	30.9	31	30.90
Day 24	30.7	30.7	30.6	30.70
Day 25	30.9	30.9	30.9	30.90
Day 26	30.6	30.6	30.6	30.60

Appendix B2 (Continued)

	Replication			Average
	1	**2**	**3**	
Day 27	30.8	30.7	30.7	30.70
Day 28	30.9	30.9	30.9	30.90
Day 29	30.7	30.7	30.6	30.70
Day 30	30.5	30.6	30.5	30.50
Day 31	30.5	30.6	30.5	30.50
Day 32	30.1	29.9	30	30.00
Day 33	29.3	29.3	29.2	29.30
Day 34	29.1	29.1	29.1	29.10
Day 35	28.6	28.5	28.6	28.60
Day 36	28.4	28.4	28.3	28.40
Day 37	27.5	27.5	27.4	27.50
Day 38	27.5	27.5	27.5	27.50
Day 39	27	26.9	27	27.00
Day 40	26.6	26.6	26.6	26.60
Day 41	26.4	26.4	26.3	26.40
Day 42	26.5	26.6	26.6	26.60
Day 43	26.5	26.4	26.4	26.40
Day 44	26.4	26.4	26.4	26.40
Day 45	25.9	25.8	25.9	25.90

Appendix Table B3 Volume of H_2SO_4 used to titrate for CO_2 generated from reactor with 50% peanut shell + 50% wastewater sludge

	Replication			**Average**
	1	**2**	**3**	
Day 1	48.4	48.5	48.4	48.40
Day 2	47.5	47.5	47.6	47.50
Day 3	47.3	47.3	47.3	47.30
Day 4	45.9	45.9	45.8	45.90
Day 5	45.7	45.6	45.7	45.70
Day 6	42.9	43	43	43.00
Day 7	39.3	39.1	39.2	39.30
Day 8	38.2	38.2	38.1	38.20
Day 9	34.1	34.4	34.3	34.30
Day 10	32	32	32	32.00
Day 11	30	30.1	30	30.00
Day 12	28.1	28.2	28.2	28.20
Day 13	25.4	25.1	25.2	25.20
Day 14	24.1	24.1	24	24.10
Day 15	22.3	22.3	22.3	22.30
Day 16	22.3	22.2	22.3	22.30
Day 17	22.3	22.4	22.3	22.30
Day 18	22	22.1	22	22.00
Day 19	22	22	22.1	22.00
Day 20	21.8	21.9	21.7	21.80
Day 21	21.8	21.7	21.8	21.80
Day 22	21.4	21.3	21.4	21.40
Day 23	20.5	20.5	20.5	20.50
Day 24	19.8	19.7	19.8	19.80
Day 25	17.2	17.3	17.3	17.30
Day 26	17.5	17.5	17.6	17.50

Appendix B3 (Continued)

	Replication			Average
	1	**2**	**3**	
Day 27	17.3	17.3	17.4	17.30
Day 28	16.4	16.3	16.4	16.40
Day 29	17.7	17.7	17.8	17.70
Day 30	17.5	17.5	17.4	17.50
Day 31	15.1	15.2	15.2	15.20
Day 32	16.4	16.4	16.5	16.40
Day 33	17.3	17.2	17.3	17.30
Day 34	14.8	14.8	14.8	14.80
Day 35	15.7	15.7	15.7	15.70
Day 36	17.3	17.2	17.3	17.30
Day 37	16.3	16.4	16.4	16.40
Day 38	17.1	17.3	17.4	17.30
Day 39	15	15	15.1	15.00
Day 40	16.7	16.8	16.8	16.80
Day 41	17	17.1	17	17.00
Day 42	14.5	14.5	14.5	14.50
Day 43	15	15	14.9	15.00
Day 44	15.7	15.6	15.7	15.70
Day 45	15	15.1	15	15.00

Appendix Table B4 Volume of H_2SO_4 used to titrate for CO_2 generated from reactor with 30% peanut shell + 70% wastewater sludge

	Replication			Average
	1	2	3	
Day 1	48.1	48	48	48.00
Day 2	47.5	47.5	47.4	47.50
Day 3	46.5	46.4	46.4	46.40
Day 4	45.2	45.2	45.2	45.20
Day 5	44.3	44.4	44.3	44.30
Day 6	42.3	42.3	42.3	42.30
Day 7	38.9	38.7	38.8	38.90
Day 8	35	35	34.9	35.00
Day 9	29.7	29.8	29.8	29.80
Day 10	28.4	28.4	28.3	28.40
Day 11	23.9	23.8	23.9	23.90
Day 12	21.4	21.4	21.3	21.40
Day 13	20.5	20.6	20.5	20.50
Day 14	20.2	20.2	20.1	20.20
Day 15	20	20	20.1	20.00
Day 16	19.4	19.5	19.5	19.50
Day 17	18.9	18.8	18.9	18.90
Day 18	19.7	19.8	19.7	19.80
Day 19	21.6	21.5	21.6	21.60
Day 20	21.1	21	21.1	21.10
Day 21	19.2	19.3	19.3	19.30
Day 22	19.8	19.8	19.7	19.80
Day 23	19.5	19.4	19.5	19.50
Day 24	17.3	17.2	17.1	17.30
Day 25	15.7	15.7	15.6	15.70
Day 26	14.8	14.8	14.7	14.80

Appendix B4 (Continued)

	Replication			Average
	1	2	3	
Day 27	14.8	14.8	14.8	14.80
Day 28	12.6	12.7	12.6	12.70
Day 29	12.7	12.7	12.6	12.70
Day 30	10.8	10.9	10.9	10.90
Day 31	11.6	11.5	11.6	11.60
Day 32	10.2	10.2	10.2	10.20
Day 33	10.9	10.8	10.9	10.90
Day 34	7.5	7.5	7.6	7.50
Day 35	7.7	7.7	7.7	7.70
Day 36	6.4	6.5	6.4	6.40
Day 37	9.9	10	10	10.00
Day 38	9.2	9.8	9.7	9.80
Day 39	10.5	10.4	10.5	10.50
Day 40	8.6	8.7	8.6	8.60
Day 41	9.5	9.5	9.4	9.50
Day 42	9.8	9.8	9.7	9.80
Day 43	8.2	8.2	8.1	8.20
Day 44	8	8	8.1	8.00
Day 45	9.3	9.3	9.3	9.30

Appendix Table B5 Volume of H_2SO_4 used to titrate for CO_2 generated from reactor with 100% wastewater sludge

	Replication			**Average**
	1	**2**	**3**	
Day 1	48	48	48.1	48.00
Day 2	46.7	46.8	46.8	46.80
Day 3	45.9	45.8	45.9	45.90
Day 4	44.3	44.5	44.4	44.30
Day 5	43.4	43.3	43.4	43.40
Day 6	41.1	41.2	41	41.10
Day 7	38.4	38.4	38.3	38.40
Day 8	34.3	34.3	34.2	34.30
Day 9	30.4	30.4	30.5	30.50
Day 10	27.7	27.6	27.7	27.70
Day 11	25.2	25.1	25.2	25.20
Day 12	20.2	20.3	20.1	20.20
Day 13	19.5	19.4	19.5	19.50
Day 14	18.4	18.3	18.4	18.40
Day 15	18.1	18.2	18.2	18.20
Day 16	18	18	17.9	18.00
Day 17	17.7	17.6	17.8	17.70
Day 18	15.2	15.2	15.1	15.20
Day 19	15	14.9	15	15.00
Day 20	13.4	13.5	13.4	13.40
Day 21	14.7	14.8	14.8	14.80
Day 22	14.8	14.8	14.8	14.80
Day 23	14.3	14.4	14.3	14.30
Day 24	13	13	12.9	13.00
Day 25	11.9	12	12	12.00
Day 26	10.9	10.8	11	10.90

Appendix B5 (Continued)

	Replication			Average
	1	**2**	**3**	
Day 27	9.7	9.8	9.8	9.80
Day 28	10.2	10.1	10.2	10.20
Day 29	10.9	10.9	10.8	10.90
Day 30	10	10	10	10.00
Day 31	9.8	9.7	9.8	9.80
Day 32	9.5	9.6	9.5	9.50
Day 33	8.5	8.6	8.6	8.60
Day 34	8	8	8.1	8.00
Day 35	8.2	8.1	8.1	8.20
Day 36	8.6	8.6	8.5	8.60
Day 37	6.6	6.5	6.4	6.60
Day 38	6.6	6.5	6.6	6.60
Day 39	8.9	8.8	8.9	8.90
Day 40	7	7	6.9	7.00
Day 41	7.7	7.6	7.7	7.70
Day 42	8.5	8.6	8.7	8.60
Day 43	7.7	7.7	7.7	7.70
Day 44	9.3	9.2	9.3	9.30
Day 45	8.6	8.6	8.5	8.60

Appendix Table B6 CO_2 generated from each reactor

CO_2 generated (g)	**Experiment**				
	1	**2**	**3**	**4**	**5**
Day 1	0.03	0.05	0.07	0.09	0.07
Day 2	0.02	0.08	0.11	0.11	0.11
Day 3	0.04	0.09	0.12	0.16	0.17
Day 4	0.03	0.15	0.18	0.21	0.24
Day 5	0.03	0.15	0.19	0.25	0.28
Day 6	0.02	0.23	0.31	0.34	0.37
Day 7	0.01	0.31	0.47	0.49	0.45
Day 8	0.02	0.41	0.52	0.66	0.51
Day 9	0.03	0.54	0.69	0.89	0.65
Day 10	0.04	0.56	0.79	0.95	0.84
Day 11	0.02	0.51	0.88	1.15	0.93
Day 12	0.04	0.64	0.96	1.26	1.06
Day 13	0.03	0.74	1.09	1.30	1.18
Day 14	0.03	0.80	1.14	1.31	1.22
Day 15	0.03	0.81	1.22	1.32	1.39
Day 16	0.03	0.82	1.22	1.34	1.40
Day 17	0.04	0.83	1.22	1.37	1.41
Day 18	0.03	0.83	1.23	1.33	1.51
Day 19	0.04	0.84	1.23	1.25	1.52
Day 20	0.04	0.84	1.24	1.27	1.58
Day 21	0.04	0.84	1.24	1.35	1.55
Day 22	0.03	0.83	1.26	1.33	1.52
Day 23	0.03	0.84	1.30	1.34	1.53
Day 24	0.03	0.85	1.33	1.44	1.54
Day 25	0.03	0.84	1.44	1.51	1.59
Day 26	0.03	0.85	1.43	1.55	1.68
Day 27	0.04	0.85	1.44	1.55	1.72

Appendix Table B6 (Continued)

CO_2 generated g)	Experiment				
	1	**2**	**3**	**4**	**5**
Day 28	0.04	0.84	1.48	1.64	1.75
Day 29	0.05	0.85	1.42	1.64	1.75
Day 30	0.04	0.86	1.43	1.72	1.75
Day 31	0.03	0.86	1.53	1.69	1.76
Day 32	0.03	0.88	1.48	1.75	1.76
Day 33	0.03	0.91	1.44	1.72	1.78
Day 34	0.03	0.92	1.55	1.87	1.81
Day 35	0.03	0.94	1.51	1.86	1.82
Day 36	0.03	0.95	1.44	1.92	1.83
Day 37	0.03	0.99	1.48	1.76	1.83
Day 38	0.03	0.99	1.44	1.77	1.84
Day 39	0.04	1.01	1.54	1.74	1.85
Day 40	0.04	1.03	1.46	1.82	1.86
Day 41	0.04	1.04	1.45	1.78	1.86
Day 42	0.04	1.03	1.56	1.77	1.86
Day 43	0.05	1.04	1.54	1.84	1.86
Day 44	0.05	1.04	1.51	1.85	1.79
Day 45	0.05	1.06	1.54	1.79	1.81

Appendix Table B7 CO_2 generated / Toluene removal

CO_2 generated/Toluene removed (g/g)	Experiment				
	1	2	3	4	5
Day 1	0.40	1.68	1.92	1.92	1.58
Day 2	0.27	1.72	2.37	2.10	1.81
Day 3	0.41	1.73	2.38	2.11	2.20
Day 4	0.29	2.07	2.39	2.16	2.20
Day 5	0.26	2.07	2.27	2.16	2.27
Day 6	0.09	1.85	2.15	2.01	2.18
Day 7	0.03	2.06	2.29	2.13	2.03
Day 8	0.06	2.12	2.18	2.29	1.72
Day 9	0.08	2.29	2.21	2.27	1.78
Day 10	0.11	2.35	2.28	2.31	2.02
Day 11	0.04	2.14	2.32	2.30	2.00
Day 12	0.07	2.22	2.24	2.29	1.95
Day 13	0.05	2.23	2.33	2.30	2.12
Day 14	0.05	2.29	2.30	2.32	2.15
Day 15	0.05	2.25	2.40	2.32	2.42
Day 16	0.05	2.31	2.35	2.37	2.49
Day 17	0.07	2.25	2.25	2.51	2.45
Day 18	0.05	2.29	2.33	2.23	2.61
Day 19	0.07	2.16	2.35	2.40	2.66
Day 20	0.07	2.20	2.36	2.50	2.63
Day 21	0.07	2.20	2.36	2.50	2.70
Day 22	0.05	2.13	2.50	2.40	2.61
Day 23	0.06	2.24	2.77	2.54	2.59
Day 24	0.06	2.35	2.79	2.55	2.54
Day 25	0.05	2.27	3.05	2.74	2.76
Day 26	0.05	2.43	2.99	2.77	2.84
Day 27	0.07	2.48	2.93	2.79	2.81

Appendix Table B7 (Continued)

CO2 generated/Toluene removed (g/g)	Experiment				
	1	**2**	**3**	**4**	**5**
Day 28	0.07	3.01	2.91	2.80	2.90
Day 29	0.10	3.02	3.03	2.82	3.12
Day 30	0.23	3.03	3.02	3.02	3.03
Day 31	0.61	2.92	3.02	2.93	3.02
Day 32	0.60	2.75	3.02	2.92	3.01
Day 33	0.73	2.66	3.08	3.02	3.02
Day 34	0.76	2.62	3.01	3.23	3.00
Day 35	2.50	2.86	3.28	3.24	3.03
Day 36	2.51	2.84	3.07	3.26	3.11
Day 37	2.60	3.02	3.05	3.06	3.18
Day 38	2.61	2.80	3.08	3.06	3.01
Day 39	3.35	2.80	3.06	3.05	3.17
Day 40	3.38	2.65	3.08	3.08	3.04
Day 41	3.19	2.64	3.05	3.09	3.07
Day 42	3.23	2.82	3.08	3.08	3.14
Day 43	4.17	2.82	3.06	3.10	3.08
Day 44	4.21	2.74	3.06	3.09	3.07
Day 45	3.96	2.89	3.03	2.97	3.07

Appendix C

Weight of mixture measurement

Appendix Table C1 Dry weight of mixture

Mixture	Before (g)	After (g)	Weight gained (g)
Peanut 100%	254	254	0
Peanut 70% + Wastewater sludge 30%	447	459	12
Peanut 50% + Wastewater sludge 50%	584	596	12
Peanut 30% + Wastewater sludge 70%	718	732	14
Wastewater sludge 100 %	923	937	14

Appendix Table C2 Wet weight of mixture

Mixture	Before (g)	After (g)	Weight gained (g)
Peanut 100%	283	285	2
Peanut 70% + Wastewater sludge 30%	678	712	34
Peanut 50% + Wastewater sludge 50%	955	996	41
Peanut 30% + Wastewater sludge 70%	1,228	1,281	53
Wastewater sludge 100 %	1,643	1,707	64

Appendix Table C3 Moisture content

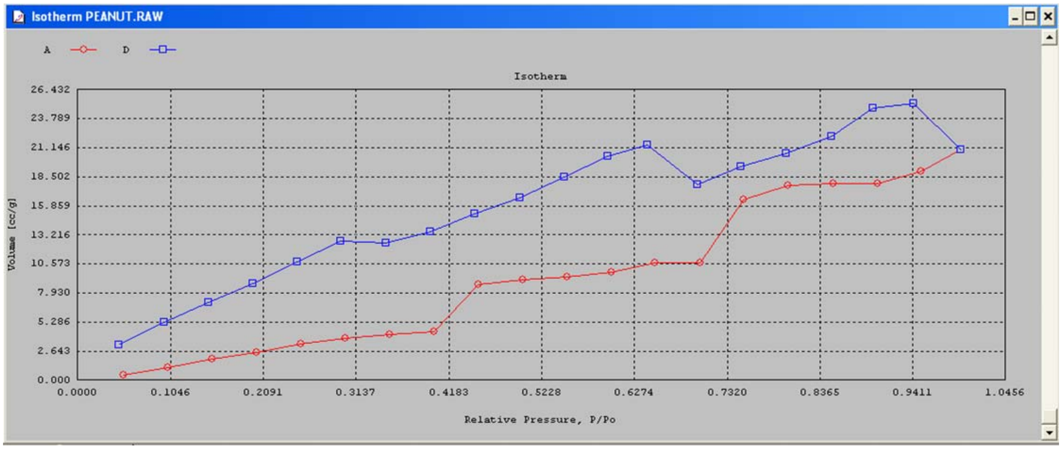
Mixture	Before (%)	After (%)	Moisture increased (g)
Peanut 100%	11.32	12.11	0.7
Peanut 70% + Wastewater sludge 30%	51.52	55.06	3.5
Peanut 50% + Wastewater sludge 50%	63.50	67.28	3.7
Peanut 30% + Wastewater sludge 70%	70.93	74.93	4.0
Wastewater sludge 100 %	78.00	82.23	4.2

Appendix D

Analysis of physical properties of the filter materials

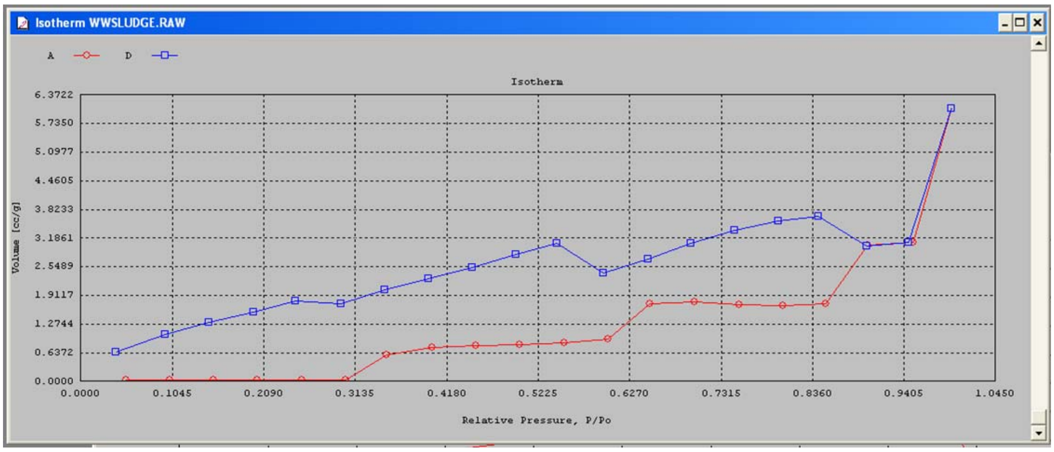
1. Isotherm

1.1 Isotherm of peanut shell



Appendix Figure D1 Isotherm of peanut shell, analyzed by Autosorp-1

1.2 Isotherm of wastewater sludge



Appendix Figure D2 Isotherm of wastewater sludge, analyzed by Autosorp-1

2. Total pore volume

2.1 Analysis data of total pore volume of peanut shell

Quantachrome Corporation
Quantachrome Autosorb Automated Gas Sorption System Report
Autosorb for Windows® Version 1.24

Description	peanut		
Sample Weight	0.0212 g		
Adsorbate	NITROGEN	Outgas Temp	250 °C
Cross-Sec Area	16.2 Å²/molec	Outgas Time	15.0 hrs
Analysis Time	235.5 min		
NonIdeality	6.580E-05	P/Po Toler	0
Molecular Wt	28.0134 g/mol	Equil Time	3
File Name	PEANUT.RAW		
Station #	1	Bath Temp.	77.35

TOTAL PORE VOLUME

Total pore volume = 3.249E-02 cc/g for

pores smaller than 4634.0 Å (Diameter),

at P/Po = 0.99585

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2.2 Analysis data of total pore volume of wastewater sludge

Quantachrome Corporation
Quantachrome Autosorb Automated Gas Sorption System Report
Autosorb for Windows® Version 1.24

Description	Solid		
Sample Weight	0.0443 g		
Adsorbate	NITROGEN	Outgas Temp	250 °C
Cross-Sec Area	16.2 Å²/molec	Outgas Time	15.0 hrs
Analysis Time	225.7 min		
NonIdeality	6.580E-05	P/Po Toler	0
Molecular Wt	28.0134 g/mol	Equil Time	3
File Name	WWSLUDGE.RAW		
Station #	1	Bath Temp.	77.35

TOTAL PORE VOLUME

Total pore volume = 9.387E-03 cc/g for

pores smaller than 4044.4 Å (Diameter),

at P/Po = 0.99524

Appendix E

Material Safety Data Sheet of Toluene

Material Safety Data Sheet of Toluene

1. Composition/information on ingredients

Synonyms

Toluene ; Methylbenzene

CAS-No.:	108-88-3	EC-Index-No.:	601-021-00-3
Molar mass:	92.14	EINECS-No.:	203-625-9
Molecular formula:	C_7H_8		

2. Hazards identification

Highly flammable. Harmful by inhalation.

3. First aid measures

After inhalation: fresh air. Keep airways free.

After skin contact: wash off with plenty of water. Remove contaminated clothing.

After eye contact: rinse out with plenty of water for at least 10 minutes with the eyelid held wide open. Summon eye specialist.

After swallowing: Paraffin oil (3 ml/kg). Sodium sulfate (1 tablespoon/1/4 l water). Summon doctor. No castor oil. No milk. No alcohol.

4. Fire-fighting measures

Suitable extinguishing media:

CO_2, foam, powder.

Special risks:

Combustible. Vapours heavier than air. Formation of explosible mixtures possible with air. Keep away from sources of ignition. Beware of backfiring.

Special protective equipment for fire fighting:

Do not stay in dangerous zone without suitable chemical protection clothing and self-contained breathing apparatus.

Other information:

Take measures to prevent electrostatic charging.
Cool container with spray water from a save distance.
Prevent fire-fighting water from entering surface water or groundwater.

5. Accidental release measures

Person-related precautionary measures:

Do not inhale vapours/aerosols. Ensure supply of fresh air in enclosed rooms.

Procedures for cleaning / absorption:

Take up with liquid-absorbent material (e.g. Chemizorb®). Forward for disposal. Clean up affected area.

Environmental-protection measures:

Do not allow to enter sewerage system.

6. Handling and storage

Handling:

No further requirements.

Storage:

Tightly closed. In a well-ventilated place. Keep away from sources of ignition and heat. At 15 °C to 25 °C.

.

7. Exposure controls/personal protection

Specific control parameter

MAK Germany (max. workplace conc.)

Toluene (Toluol)	50 ml/m^3 or 190 mg/m^3

Personal protective equipment:

Respiratory protection:	required when vapours/aerosols are generated.
Eye protection:	required
Hand protection:	required
Industrial hygiene:	Change contaminated clothing. Apply skin-protective barrier cream. Wash hands and face after working with substance.

8. Physical and chemical properties

Form:		liquid
Colour:		colourless
Odour:		characteristic
pH value		Not avalible
Melting temperature		-95 °C
Boiling temperature		111 °C
Ignition temperature		535 °C
Flash point		6 °C
Explosion limits	lower	1.2 Vol%
	upper	7.0 Vol%
Vapour pressure		29 mbar
Density		0.87 g/cm^3
Solubility in water		0.5 g/l
log P(oct):		2.69

9. Stability and reactivity

Conditions to be avoided

Strong heating.

Substances to be avoided

halogen-halogen compounds , nitric acid , nitrogen oxides , organic nitro compounds , oxidizing agent , uranium hexafluoride , sulfur / heat

Hazardous decomposition products

no information available

Further information

highly inflammable ;
unsuitable working materials: various plastics , rubber
Explosible with air in a vaporous/gaseous state.

10. Toxicological information

Acute toxicity

LD_{50} (oral, rat): 636 mg/kg
LC_{50} (inhalation, rat): 49 g/m^3 /4 h

Subacute to chronic toxicity

An embryotoxic effect need not be feared when the threshold limit value is observed.

Further toxicological information

After inhalation: Irritation symptoms in the respiratory tract.
After skin contact: Irritations. After long-term exposure to the chemical: dermatitis Degreasing effect on the skin, possibly followed by secondary inflammation. Danger of skin absorption.
After eye contact: Irritations. mucosal irritations

Swallowing causes nausea and vomiting. Risk of aspiration upon vomiting. absorption Systemic effects: After absorption of large quantities: CNS disorders , inebriation , spasms , unconsciousness , respiratory arrest , cardiovascular failure

Further data

The product should be handled with the care usual when dealing with chemicals.

11. Ecological information

Biologic degradation:

Water-dissolved constituents biodegradable.

Behavior in environmental compartments:

Distribution: log P(oct):: 2.69

Low bioaccumulation potential.

Evaluation number (FRG) (bacteria): 4.5

Evaluation number (FRG) (fish): 4.2

Evaluation number (FRG) (mammal): 1

Ecotoxic effects:

Biological effects: Toxic for aquatic organisms Toxic effect on fish and plankton. Change in the flavour characteristics of fish protein. Risk of formation of explosive vapours above water surface.

Fish toxicity: L.idus LC_{50}: 70 mg/l ;

Daphnia toxicity: Daphnia magna EC_{50}: 270 mg/l ;

Bacterial toxicity: Ps.pudita EC_0: 29 mg/l ;

Further ecologic data:

Degradability:

BOD_5: 0.86 g/g ;

COD: 0.7 g/g ;

ThOD: 3.13 g/g

Do not allow to enter waters, waste water, or soil!

12. Disposal considerations

Product:

There are no uniform EC Regulations for the disposal of chemicals or residues. Chemical residues generally count as special waste. The disposal of the latter is regulated in the EC member countries through corresponding laws and regulations. We recommend that you contact either the authorities in charge or approved waste disposal companies which will advise you on how to dispose of special waste.

Packaging:

Disposal in compliance with official regulations. Handle contaminated packaging in the same way as the substance itself. If not officially specified differently, non-contaminated packaging may be treated like household waste or recycled.

13. Transport information

Transport over land ADR/RID and GGVS/GGVE (Germany)

GGVS/GGVE class:	3	Number and letter:	3b
ADR/RID class:	3	Number and letter:	3b
Name of material:	1294 TOLUEN		

River transport ADN/ADNR

not examined

Sea transport IMDG

IMDG class:	3.2	UN-No.:	1294	Packaging group:	II
Ems:	3-07	MFAG:	310		
Correct technical name:	TOLUENE				

Air transport ICAO-TI and IATA-DGR

ICAO/IATA class:	3	UN/ID-No.:	1294	Packaging group:	II
Correct technical name:	TOLUENE				

The transport regulations are cited according to international regulations and in the form applicable in Germany (GGVS/GGVE). Possible national deviations in other countries are not considered.

14. Regulatory information

Labelling according to EC Directives

Symbol:	F	Highly flammable immediately and show this container or label.
	Xn	Harmful immediately and show this container or label.
R-phrases:	R 11-20	Highly flammable. Harmful by inhalation.
S-phrases:	S 16-25-29-33	Keep away from sources of ignition - No smoking. Avoid contact with eyes. Do not empty into drains. Take precautionary measures against static discharges.
EC-No.:	203-625-9	EC label

German regulations

Water pollution class	2	(polluting substance)

15. Other information

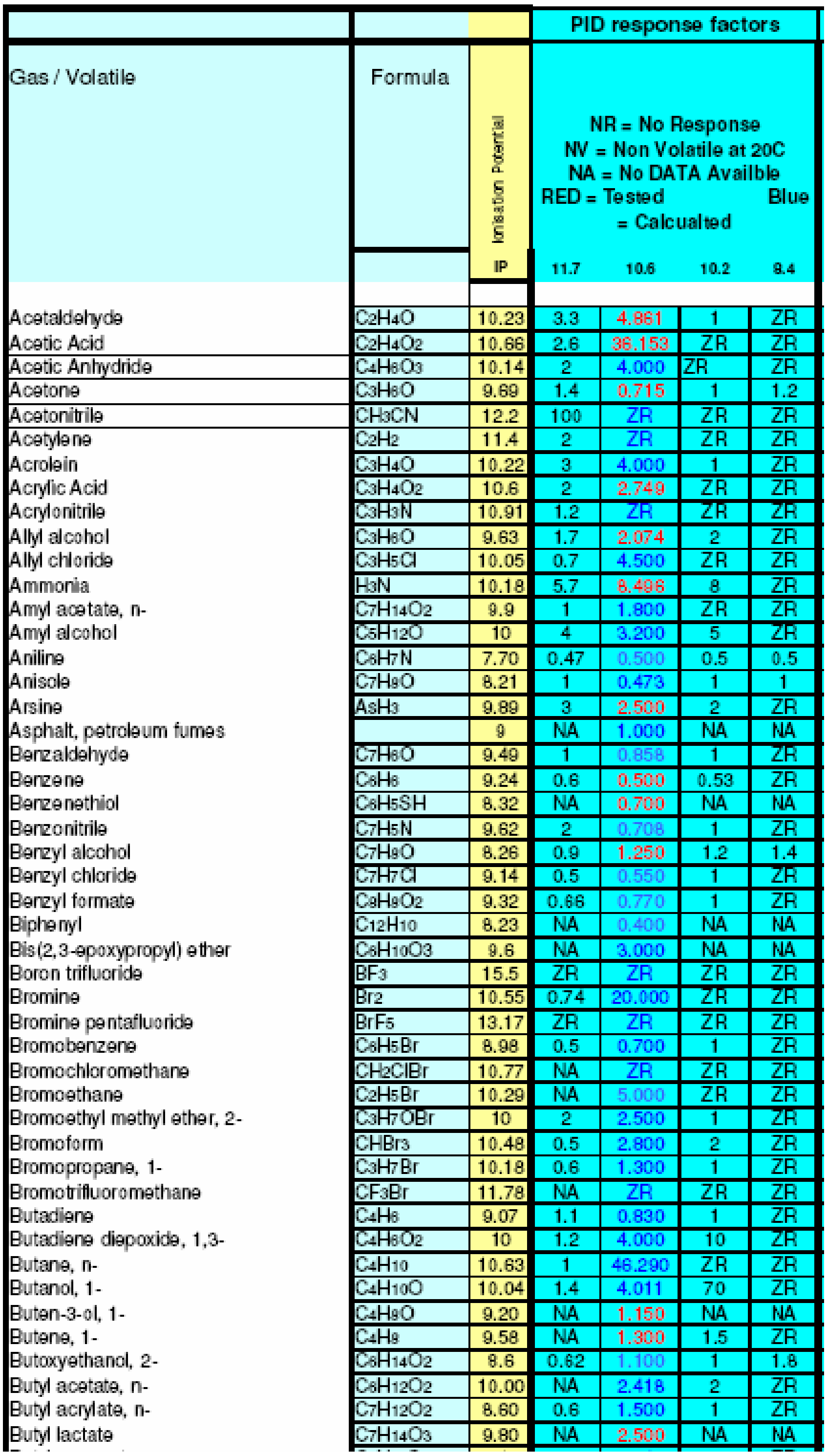
Reason for alteration

See chapter 7 (Specific control parameter.)

Appendix F

Response factor for know substance

Response Factor for known substance

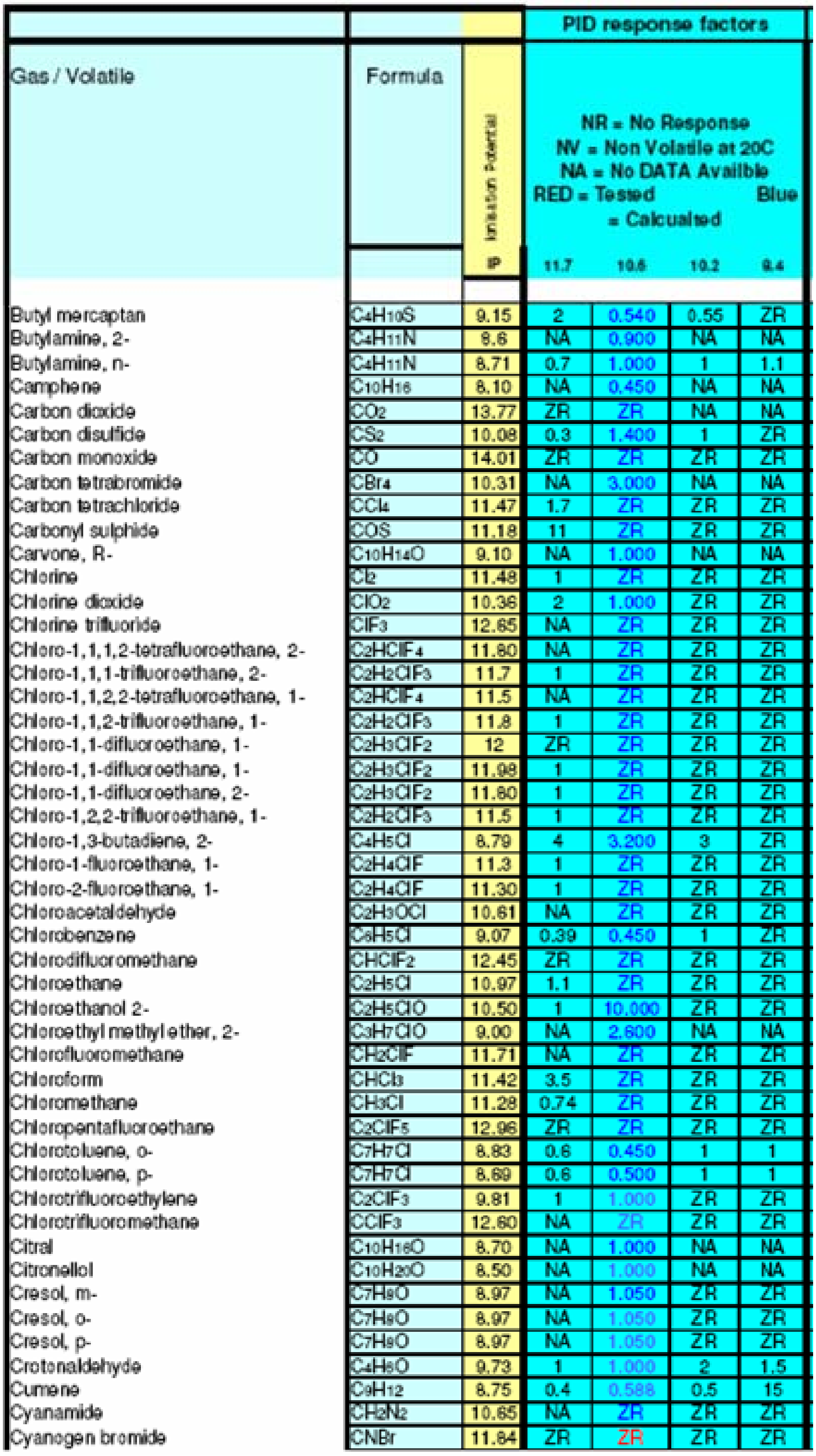


PID response factors

NR = No Response
NV = Non Volatile at 20C
NA = No DATA Availble
RED = Tested Blue = Calcualted

Gas / Volatile	Formula	Ionisation Potential IP	11.7	10.6	10.2	9.4
Acetaldehyde	C_2H_4O	10.23	3.3	4.861	1	ZR
Acetic Acid	$C_2H_4O_2$	10.66	2.6	36.153	ZR	ZR
Acetic Anhydride	$C_4H_6O_3$	10.14	2	4.000	ZR	ZR
Acetone	C_3H_6O	9.69	1.4	0.715	1	1.2
Acetonitrile	CH_3CN	12.2	100	ZR	ZR	ZR
Acetylene	C_2H_2	11.4	2	ZR	ZR	ZR
Acrolein	C_3H_4O	10.22	3	4.000	1	ZR
Acrylic Acid	$C_3H_4O_2$	10.6	2	2.749	ZR	ZR
Acrylonitrile	C_3H_3N	10.91	1.2	ZR	ZR	ZR
Allyl alcohol	C_3H_6O	9.63	1.7	2.074	2	ZR
Allyl chloride	C_3H_5Cl	10.05	0.7	4.500	ZR	ZR
Ammonia	H_3N	10.18	5.7	8.496	8	ZR
Amyl acetate, n-	$C_7H_{14}O_2$	9.9	1	1.800	ZR	ZR
Amyl alcohol	$C_5H_{12}O$	10	4	3.200	5	ZR
Aniline	C_6H_7N	7.70	0.47	0.500	0.5	0.5
Anisole	C_7H_8O	8.21	1	0.473	1	1
Arsine	AsH_3	9.89	3	2.500	2	ZR
Asphalt, petroleum fumes		9	NA	1.000	NA	NA
Benzaldehyde	C_7H_6O	9.49	1	0.858	1	ZR
Benzene	C_6H_6	9.24	0.6	0.500	0.53	ZR
Benzenethiol	C_6H_5SH	8.32	NA	0.700	NA	NA
Benzonitrile	C_7H_5N	9.62	2	0.708	1	ZR
Benzyl alcohol	C_7H_8O	8.26	0.9	1.250	1.2	1.4
Benzyl chloride	C_7H_7Cl	9.14	0.5	0.550	1	ZR
Benzyl formate	$C_8H_8O_2$	9.32	0.66	0.770	1	ZR
Biphenyl	$C_{12}H_{10}$	8.23	NA	0.400	NA	NA
Bis(2,3-epoxypropyl) ether	$C_6H_{10}O_3$	9.6	NA	3.000	NA	NA
Boron trifluoride	BF_3	15.5	ZR	ZR	ZR	ZR
Bromine	Br_2	10.55	0.74	20.000	ZR	ZR
Bromine pentafluoride	BrF_5	13.17	ZR	ZR	ZR	ZR
Bromobenzene	C_6H_5Br	8.98	0.5	0.700	1	ZR
Bromochloromethane	CH_2ClBr	10.77	NA	ZR	ZR	ZR
Bromoethane	C_2H_5Br	10.29	NA	5.000	ZR	ZR
Bromoethyl methyl ether, 2-	C_3H_7OBr	10	2	2.500	1	ZR
Bromoform	$CHBr_3$	10.48	0.5	2.800	2	ZR
Bromopropane, 1-	C_3H_7Br	10.18	0.6	1.300	1	ZR
Bromotrifluoromethane	CF_3Br	11.78	NA	ZR	ZR	ZR
Butadiene	C_4H_6	9.07	1.1	0.830	1	ZR
Butadiene diepoxide, 1,3-	$C_4H_6O_2$	10	1.2	4.000	10	ZR
Butane, n-	C_4H_{10}	10.63	1	46.290	ZR	ZR
Butanol, 1-	$C_4H_{10}O$	10.04	1.4	4.011	70	ZR
Buten-3-ol, 1-	C_4H_8O	9.20	NA	1.150	NA	NA
Butene, 1-	C_4H_8	9.58	NA	1.300	1.5	ZR
Butoxyethanol, 2-	$C_6H_{14}O_2$	8.6	0.62	1.100	1	1.8
Butyl acetate, n-	$C_6H_{12}O_2$	10.00	NA	2.418	2	ZR
Butyl acrylate, n-	$C_7H_{12}O_2$	8.60	0.6	1.500	1	ZR
Butyl lactate	$C_7H_{14}O_3$	9.80	NA	2.500	NA	NA

Appendix Figure F Response factor for known substance from Photo Ionization Detector Manufacturer

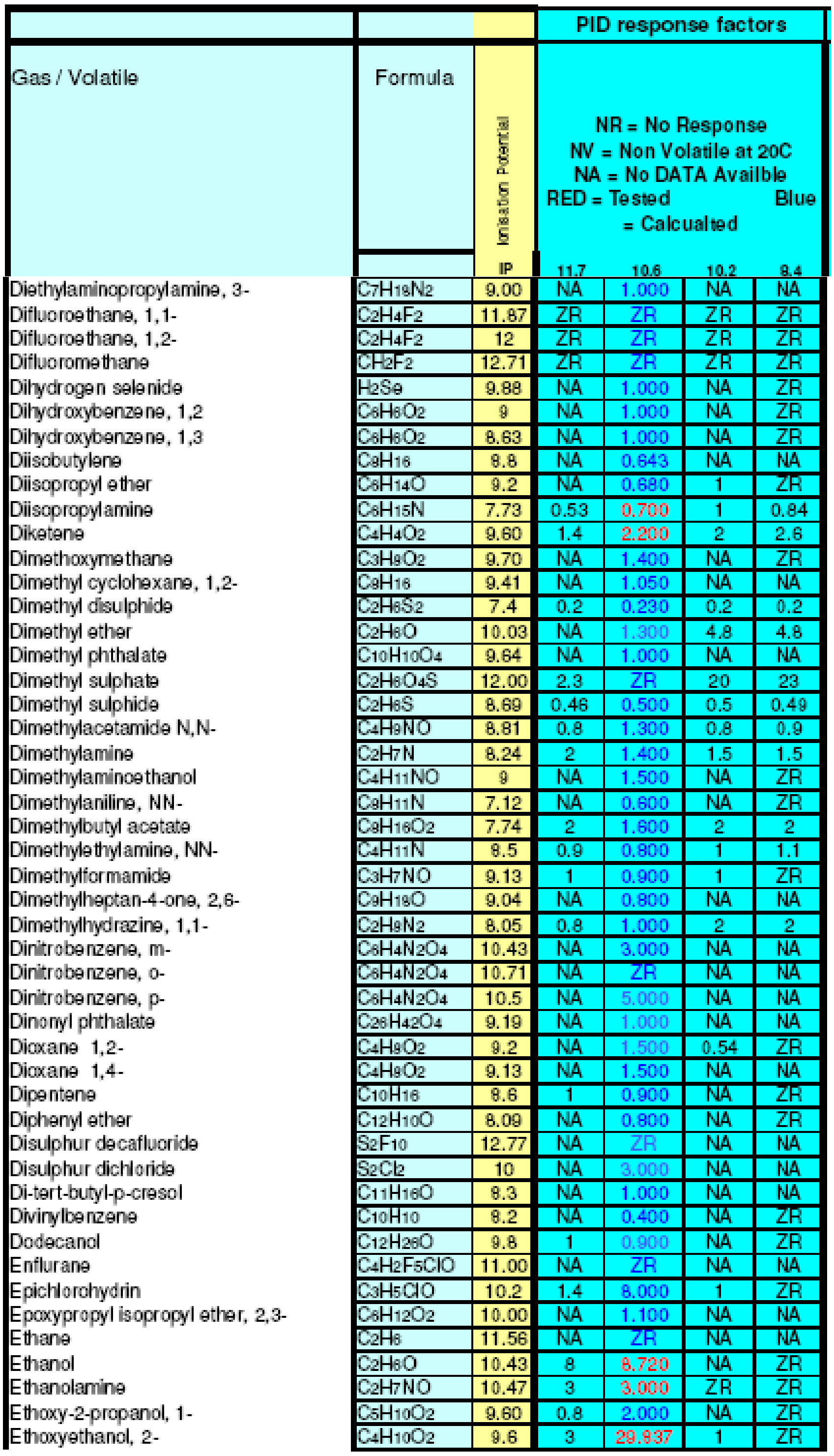


Gas / Volatile	Formula	Ionization Potential IP	PID response factors NR = No Response NV = Non Volatile at 20C NA = No DATA Availble RED = Tested Blue = Calcualted			
			11.7	10.6	10.2	9.4
Butyl mercaptan	$C_4H_{10}S$	9.15	2	0.540	0.55	ZR
Butylamine, 2-	$C_4H_{11}N$	8.6	NA	0.900	NA	NA
Butylamine, n-	$C_4H_{11}N$	8.71	0.7	1.000	1	1.1
Camphene	$C_{10}H_{16}$	8.10	NA	0.450	NA	NA
Carbon dioxide	CO_2	13.77	ZR	ZR	NA	NA
Carbon disulfide	CS_2	10.08	0.3	1.400	1	ZR
Carbon monoxide	CO	14.01	ZR	ZR	ZR	ZR
Carbon tetrabromide	CBr_4	10.31	NA	3.000	NA	NA
Carbon tetrachloride	CCl_4	11.47	1.7	ZR	ZR	ZR
Carbonyl sulphide	COS	11.18	11	ZR	ZR	ZR
Carvone, R-	$C_{10}H_{14}O$	9.10	NA	1.000	NA	NA
Chlorine	Cl_2	11.48	1	ZR	ZR	ZR
Chlorine dioxide	ClO_2	10.36	2	1.000	ZR	ZR
Chlorine trifluoride	ClF_3	12.65	NA	ZR	ZR	ZR
Chloro-1,1,1,2-tetrafluoroethane, 2-	C_2HClF_4	11.80	NA	ZR	ZR	ZR
Chloro-1,1,1-trifluoroethane, 2-	$C_2H_2ClF_3$	11.7	1	ZR	ZR	ZR
Chloro-1,1,2,2-tetrafluoroethane, 1-	C_2HClF_4	11.5	NA	ZR	ZR	ZR
Chloro-1,1,2-trifluoroethane, 1-	$C_2H_2ClF_3$	11.8	1	ZR	ZR	ZR
Chloro-1,1-difluoroethane, 1-	$C_2H_3ClF_2$	12	ZR	ZR	ZR	ZR
Chloro-1,1-difluoroethane, 1-	$C_2H_3ClF_2$	11.98	1	ZR	ZR	ZR
Chloro-1,1-difluoroethane, 2-	$C_2H_3ClF_2$	11.80	1	ZR	ZR	ZR
Chloro-1,2,2-trifluoroethane, 1-	$C_2H_2ClF_3$	11.5	1	ZR	ZR	ZR
Chloro-1,3-butadiene, 2-	C_4H_5Cl	8.79	4	3.200	3	ZR
Chloro-1-fluoroethane, 1-	C_2H_4ClF	11.3	1	ZR	ZR	ZR
Chloro-2-fluoroethane, 1-	C_2H_4ClF	11.30	1	ZR	ZR	ZR
Chloroacetaldehyde	C_2H_3OCl	10.61	NA	ZR	ZR	ZR
Chlorobenzene	C_6H_5Cl	9.07	0.39	0.450	1	ZR
Chlorodifluoromethane	$CHClF_2$	12.45	ZR	ZR	ZR	ZR
Chloroethane	C_2H_5Cl	10.97	1.1	ZR	ZR	ZR
Chloroethanol 2-	C_2H_5ClO	10.50	1	10.000	ZR	ZR
Chloroethyl methyl ether, 2-	C_3H_7ClO	9.00	NA	2.600	NA	NA
Chlorofluoromethane	CH_2ClF	11.71	NA	ZR	ZR	ZR
Chloroform	$CHCl_3$	11.42	3.5	ZR	ZR	ZR
Chloromethane	CH_3Cl	11.28	0.74	ZR	ZR	ZR
Chloropentafluoroethane	C_2ClF_5	12.96	ZR	ZR	ZR	ZR
Chlorotoluene, o-	C_7H_7Cl	8.83	0.6	0.450	1	1
Chlorotoluene, p-	C_7H_7Cl	8.69	0.6	0.500	1	1
Chlorotrifluoroethylene	C_2ClF_3	9.81	1	1.000	ZR	ZR
Chlorotrifluoromethane	$CClF_3$	12.60	NA	ZR	ZR	ZR
Citral	$C_{10}H_{16}O$	8.70	NA	1.000	NA	NA
Citronellol	$C_{10}H_{20}O$	8.50	NA	1.000	NA	NA
Cresol, m-	C_7H_8O	8.97	NA	1.050	ZR	ZR
Cresol, o-	C_7H_8O	8.97	NA	1.050	ZR	ZR
Cresol, p-	C_7H_8O	8.97	NA	1.050	ZR	ZR
Crotonaldehyde	C_4H_6O	9.73	1	1.000	2	1.5
Cumene	C_9H_{12}	8.75	0.4	0.588	0.5	15
Cyanamide	CH_2N_2	10.65	NA	ZR	ZR	ZR
Cyanogen bromide	$CNBr$	11.84	ZR	ZR	ZR	ZR

Appendix Figure F (Continued)

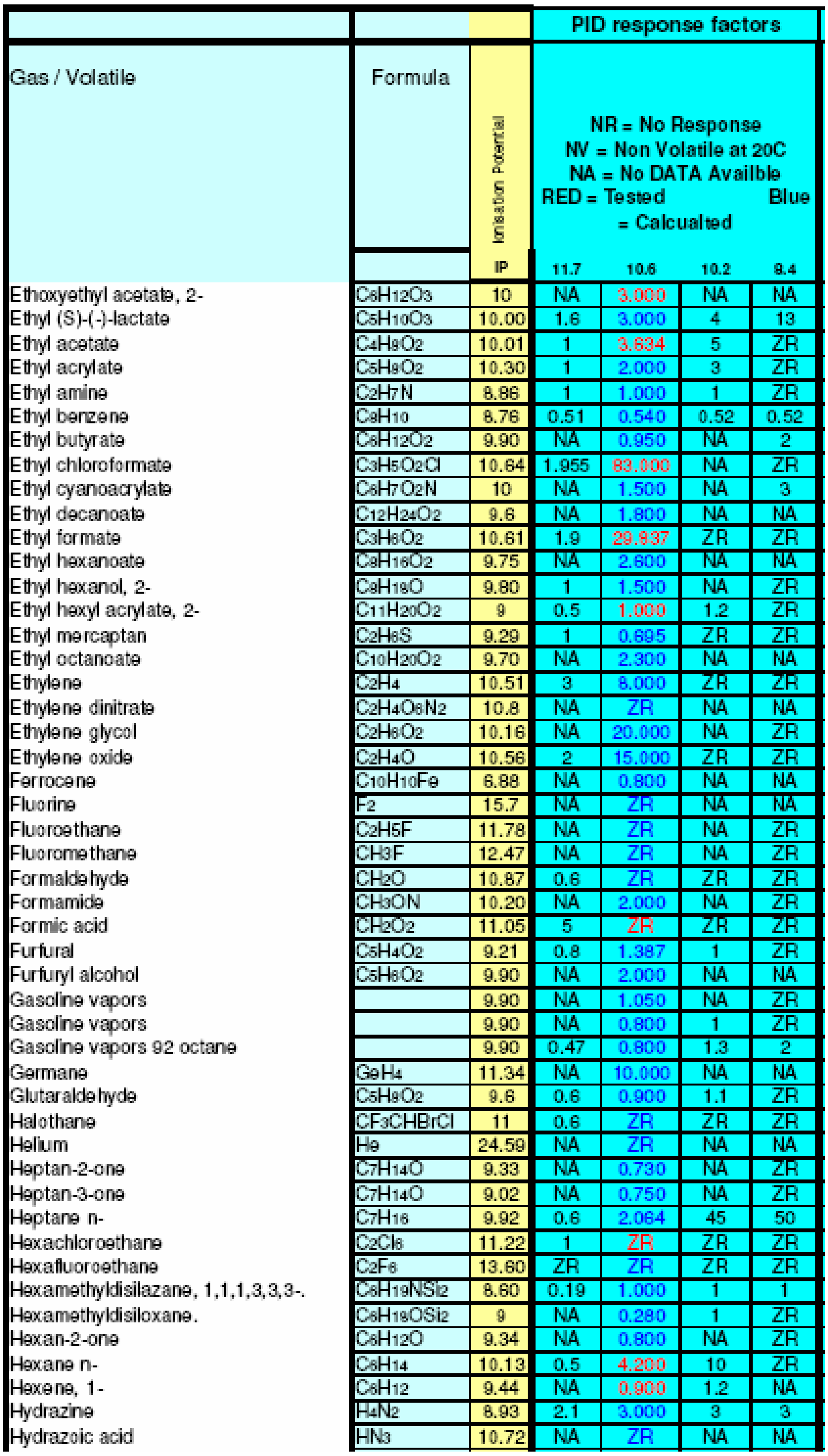
Gas / Volatile	Formula	Ionisation Potential	PID response factors NR = No Response NV = Non Volatile at 20C NA = No DATA Availble RED = Tested Blue = Calcualted			
		IP	11.7	10.6	10.2	9.4
Cyanogen chloride	$CNCl$	12.49	ZR	ZR	ZR	ZR
Cyclohexane	C_6H_{12}	9.86	0.64	1.162	2	3.3
Cyclohexanol	$C_6H_{12}O$	10.00	1.1	2.906	1	ZR
Cyclohexanone	$C_6H_{10}O$	9.40	0.7	1.039	1	ZR
Cyclohexene	C_6H_{10}	8.95	1	0.750	1	ZR
Cyclohexylamine	$C_6H_{13}N$	8.37	1	0.981	1	1
Cyclopentane	C_5H_{10}	10.52	0.6	4.000	ZR	ZR
Decane, n-	$C_{10}H_{22}$	9.65	0.35	1.043	2	ZR
Diacetone alcohol	$C_6H_{12}O_2$	9.00	NA	0.800	NA	NA
Dibenzoyl peroxide	$C_{14}H_{10}O_4$	9.00	NA	0.800	NA	NA
Diborane	B_2H_6	11.38	NA	ZR	ZR	ZR
Dibromochloromethane	$CHBr_2Cl$	10.59	0.7	10.000	5	ZR
Dibromodifluoromethane	CF_2Br_2	11.07	NA	ZR	ZR	ZR
Dibromoethane 1,2-	$C_2H_4Br_2$	9.45	0.6	2.000	ZR	ZR
Dibromotetrafluoroethane, 1,2-	$C_2F_4Br_2$	11.1	NA	ZR	ZR	ZR
Dibutyl hydrogen phosphate	$HC_8H_{18}PO_4$	10.00	NA	4.000	NA	NA
Dichloro-1,1,1-trifluoroethane, 2,2-	$C_2HCl_2F_3$	11	NA	ZR	ZR	ZR
Dichloro-1,1-difluoroethane, 1,2-	$C_2H_2Cl_2F_2$	11	1	ZR	ZR	ZR
Dichloro-1,2,2-trifluoroethane, 1,2-	$C_2HCl_2F_3$	11	NA	ZR	ZR	ZR
Dichloro-1,2-difluoroethane, 1,2-	$C_2H_2Cl_2F_2$	11	1	ZR	ZR	ZR
Dichloro-1-fluoroethane, 1,1-	$C_2H_3Cl_2F$	11	2	ZR	ZR	ZR
Dichloro-1-fluoroethane, 1,1-	$C_2H_3Cl_2F$	11	1	ZR	ZR	ZR
Dichloro-1-fluoroethane, 1,2-	$C_2H_3Cl_2F$	11	1	ZR	ZR	ZR
Dichloro-1-propene, 2,3-	$C_3H_4Cl_2$	10.50	0.7	1.400	1	1.9
Dichloro-2,2,-difluoroethane, 1,1-	$C_2H_2Cl_2F_2$	11.5	10	ZR	ZR	ZR
Dichloroacetylene	C_2Cl_2	9.9	NA	5.000	NA	NA
Dichlorobenzene o-	$C_6H_4Cl_2$	9.06	0.38	0.500	0.5	ZR
Dichlorodifluoromethane	CCl_2F_2	11.75	ZR	ZR	ZR	ZR
Dichloroethane 1,2-	$C_2H_4Cl_2$	11.05	0.6	ZR	ZR	ZR
Dichloroethane, 1,1-	$C_2H_4Cl_2$	11.06	2	ZR	ZR	ZR
Dichloroethene, 1,1-	$C_2H_2Cl_2$	10.00	1	0.950	1	ZR
Dichloroethene, cis-1,2-	$C_2H_2Cl_2$	9.66	1	0.800	1	ZR
Dichloroethene, trans-1,2-	$C_2H_2Cl_2$	9.65	0.3	0.700	1	ZR
Dichloroethylene 1,2-	$C_2H_2Cl_2$	9.65	NA	0.750	NA	ZR
Dichlorofluoromethane	$CHFCl_2$	12.39	ZR	ZR	ZR	ZR
Dichloromethane	CH_2Cl_2	11.32	0.89	39.000	ZR	ZR
Dichloropropane, 1,2-	$C_3H_6Cl_2$	10.87	0.7	ZR	1	ZR
Dichlorotetrafluoroethane, 1,1-	$C_2Cl_2F_4$	12.2	ZR	ZR	ZR	ZR
Dichlorotetrafluoroethane, 1,2-	$C_2Cl_2F_4$	12.20	ZR	ZR	ZR	ZR
Dicyclopentadiene	$C_{10}H_{12}$	8.00	1	0.900	NA	ZR
Diesel Fuel		8	0.4	0.750	3	10
Diethyl ether	$C_4H_{10}O$	9.53	1.9	0.884	ZR	ZR
Diethyl maleate	$C_8H_{12}O_4$	10	NA	2.000	NA	NA
Diethyl phthalate	$C_{12}H_{14}O_4$	9	NA	1.000	NA	NA
Diethyl sulphate	$C_4H_{10}SO_4$		NA	3.000	NA	NA
Diethyl sulphide	$C_4H_{10}S$	8.43	1	0.550	1	3
Diethylamine	$C_4H_{11}N$	8.01	1	1.000	1	1
Diethylaminoethanol, 2-	$C_6H_{15}ON$	9	NA	2.700	NA	NA

Appendix Figure F (Continued)



Gas / Volatile	Formula	Ionisation Potential	PID response factors			
			NR = No Response NV = Non Volatile at 20C NA = No DATA Availble RED = Tested Blue = Calcualted			
		IP	11.7	10.6	10.2	9.4
Diethylaminopropylamine, 3-	$C_7H_{18}N_2$	9.00	NA	1.000	NA	NA
Difluoroethane, 1,1-	$C_2H_4F_2$	11.87	ZR	ZR	ZR	ZR
Difluoroethane, 1,2-	$C_2H_4F_2$	12	ZR	ZR	ZR	ZR
Difluoromethane	CH_2F_2	12.71	ZR	ZR	ZR	ZR
Dihydrogen selenide	H_2Se	9.88	NA	1.000	NA	ZR
Dihydroxybenzene, 1,2	$C_6H_6O_2$	9	NA	1.000	NA	ZR
Dihydroxybenzene, 1,3	$C_6H_6O_2$	8.63	NA	1.000	NA	ZR
Diisobutylene	C_8H_{16}	8.8	NA	0.643	NA	NA
Diisopropyl ether	$C_6H_{14}O$	9.2	NA	0.680	1	ZR
Diisopropylamine	$C_6H_{15}N$	7.73	0.53	0.700	1	0.84
Diketene	$C_4H_4O_2$	9.60	1.4	2.200	2	2.6
Dimethoxymethane	$C_3H_8O_2$	9.70	NA	1.400	NA	ZR
Dimethyl cyclohexane, 1,2-	C_8H_{16}	9.41	NA	1.050	NA	NA
Dimethyl disulphide	$C_2H_6S_2$	7.4	0.2	0.230	0.2	0.2
Dimethyl ether	C_2H_6O	10.03	NA	1.300	4.8	4.8
Dimethyl phthalate	$C_{10}H_{10}O_4$	9.64	NA	1.000	NA	NA
Dimethyl sulphate	$C_2H_6O_4S$	12.00	2.3	ZR	20	23
Dimethyl sulphide	C_2H_6S	8.69	0.46	0.500	0.5	0.49
Dimethylacetamide N,N-	C_4H_9NO	8.81	0.8	1.300	0.8	0.9
Dimethylamine	C_2H_7N	8.24	2	1.400	1.5	1.5
Dimethylaminoethanol	$C_4H_{11}NO$	9	NA	1.500	NA	ZR
Dimethylaniline, NN-	$C_8H_{11}N$	7.12	NA	0.600	NA	ZR
Dimethylbutyl acetate	$C_8H_{16}O_2$	7.74	2	1.600	2	2
Dimethylethylamine, NN-	$C_4H_{11}N$	8.5	0.9	0.800	1	1.1
Dimethylformamide	C_3H_7NO	9.13	1	0.900	1	ZR
Dimethylheptan-4-one, 2,6-	$C_9H_{18}O$	9.04	NA	0.800	NA	NA
Dimethylhydrazine, 1,1-	$C_2H_8N_2$	8.05	0.8	1.000	2	2
Dinitrobenzene, m-	$C_6H_4N_2O_4$	10.43	NA	3.000	NA	NA
Dinitrobenzene, o-	$C_6H_4N_2O_4$	10.71	NA	ZR	NA	NA
Dinitrobenzene, p-	$C_6H_4N_2O_4$	10.5	NA	5.000	NA	NA
Dinonyl phthalate	$C_{26}H_{42}O_4$	9.19	NA	1.000	NA	NA
Dioxane 1,2-	$C_4H_8O_2$	9.2	NA	1.500	0.54	ZR
Dioxane 1,4-	$C_4H_8O_2$	9.13	NA	1.500	NA	NA
Dipentene	$C_{10}H_{16}$	8.6	1	0.900	NA	ZR
Diphenyl ether	$C_{12}H_{10}O$	8.09	NA	0.800	NA	ZR
Disulphur decafluoride	S_2F_{10}	12.77	NA	ZR	NA	NA
Disulphur dichloride	S_2Cl_2	10	NA	3.000	NA	NA
Di-tert-butyl-p-cresol	$C_{11}H_{16}O$	8.3	NA	1.000	NA	NA
Divinylbenzene	$C_{10}H_{10}$	8.2	NA	0.400	NA	ZR
Dodecanol	$C_{12}H_{26}O$	9.8	1	0.900	NA	ZR
Enflurane	$C_4H_2F_5ClO$	11.00	NA	ZR	NA	NA
Epichlorohydrin	C_3H_5ClO	10.2	1.4	8.000	1	ZR
Epoxypropyl isopropyl ether, 2,3-	$C_6H_{12}O_2$	10.00	NA	1.100	NA	NA
Ethane	C_2H_6	11.56	NA	ZR	NA	NA
Ethanol	C_2H_6O	10.43	8	8.720	NA	ZR
Ethanolamine	C_2H_7NO	10.47	3	3.000	ZR	ZR
Ethoxy-2-propanol, 1-	$C_5H_{10}O_2$	9.60	0.8	2.000	NA	ZR
Ethoxyethanol, 2-	$C_4H_{10}O_2$	9.6	3	29.837	1	ZR

Appendix Figure F (Continued)

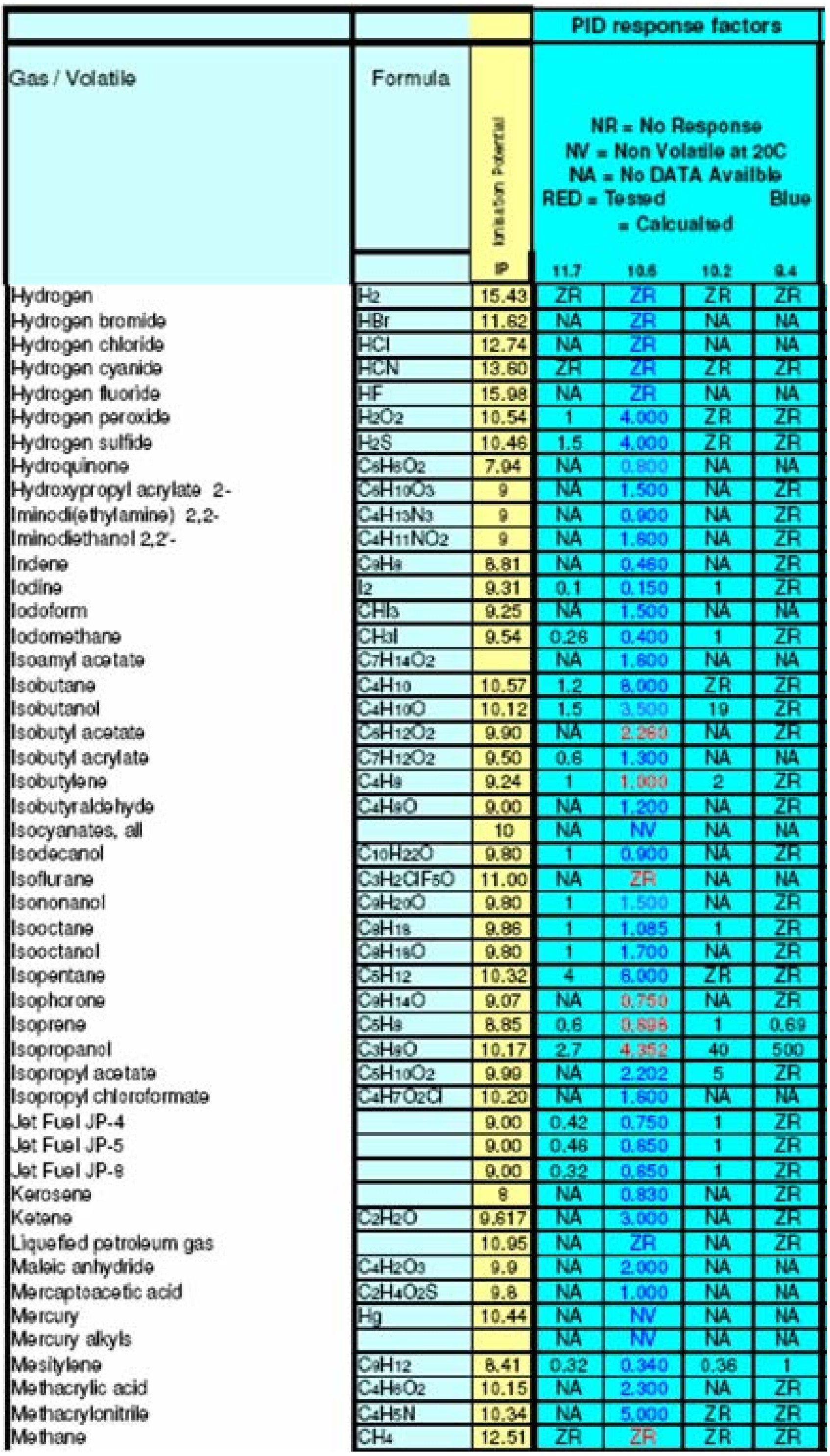


PID response factors

NR = No Response
NV = Non Volatile at 20C
NA = No DATA Availble
RED = Tested Blue = Calcualted

Gas / Volatile	Formula	Ionisation Potential IP	11.7	10.6	10.2	9.4
Ethoxyethyl acetate, 2-	$C_6H_{12}O_3$	10	NA	3.000	NA	NA
Ethyl (S)-(-)-lactate	$C_5H_{10}O_3$	10.00	1.6	3.000	4	13
Ethyl acetate	$C_4H_8O_2$	10.01	1	3.634	5	ZR
Ethyl acrylate	$C_5H_8O_2$	10.30	1	2.000	3	ZR
Ethyl amine	C_2H_7N	8.86	1	1.000	1	ZR
Ethyl benzene	C_8H_{10}	8.76	0.51	0.540	0.52	0.52
Ethyl butyrate	$C_6H_{12}O_2$	9.90	NA	0.950	NA	2
Ethyl chloroformate	$C_3H_5O_2Cl$	10.64	1.955	83.000	NA	ZR
Ethyl cyanoacrylate	$C_6H_7O_2N$	10	NA	1.500	NA	3
Ethyl decanoate	$C_{12}H_{24}O_2$	9.6	NA	1.800	NA	NA
Ethyl formate	$C_3H_6O_2$	10.61	1.9	29.937	ZR	ZR
Ethyl hexanoate	$C_8H_{16}O_2$	9.75	NA	2.600	NA	NA
Ethyl hexanol, 2-	$C_8H_{18}O$	9.80	1	1.500	NA	ZR
Ethyl hexyl acrylate, 2-	$C_{11}H_{20}O_2$	9	0.5	1.000	1.2	ZR
Ethyl mercaptan	C_2H_6S	9.29	1	0.695	ZR	ZR
Ethyl octanoate	$C_{10}H_{20}O_2$	9.70	NA	2.300	NA	NA
Ethylene	C_2H_4	10.51	3	8.000	ZR	ZR
Ethylene dinitrate	$C_2H_4O_6N_2$	10.8	NA	ZR	NA	NA
Ethylene glycol	$C_2H_6O_2$	10.16	NA	20.000	NA	ZR
Ethylene oxide	C_2H_4O	10.56	2	15.000	ZR	ZR
Ferrocene	$C_{10}H_{10}Fe$	6.88	NA	0.800	NA	NA
Fluorine	F_2	15.7	NA	ZR	NA	NA
Fluoroethane	C_2H_5F	11.78	NA	ZR	NA	ZR
Fluoromethane	CH_3F	12.47	NA	ZR	NA	ZR
Formaldehyde	CH_2O	10.87	0.6	ZR	ZR	ZR
Formamide	CH_3ON	10.20	NA	2.000	NA	ZR
Formic acid	CH_2O_2	11.05	5	ZR	ZR	ZR
Furfural	$C_5H_4O_2$	9.21	0.8	1.387	1	ZR
Furfuryl alcohol	$C_5H_6O_2$	9.90	NA	2.000	NA	NA
Gasoline vapors		9.90	NA	1.050	NA	ZR
Gasoline vapors		9.90	NA	0.800	1	ZR
Gasoline vapors 92 octane		9.90	0.47	0.800	1.3	2
Germane	GeH_4	11.34	NA	10.000	NA	NA
Glutaraldehyde	$C_5H_8O_2$	9.6	0.6	0.900	1.1	ZR
Halothane	$CF_3CHBrCl$	11	0.6	ZR	ZR	ZR
Helium	He	24.59	NA	ZR	NA	NA
Heptan-2-one	$C_7H_{14}O$	9.33	NA	0.730	NA	ZR
Heptan-3-one	$C_7H_{14}O$	9.02	NA	0.750	NA	ZR
Heptane n-	C_7H_{16}	9.92	0.6	2.064	45	50
Hexachloroethane	C_2Cl_6	11.22	1	ZR	ZR	ZR
Hexafluoroethane	C_2F_6	13.60	ZR	ZR	ZR	ZR
Hexamethyldisilazane, 1,1,1,3,3,3-.	$C_6H_{19}NSi_2$	8.60	0.19	1.000	1	1
Hexamethyldisiloxane.	$C_6H_{18}OSi_2$	9	NA	0.280	1	ZR
Hexan-2-one	$C_6H_{12}O$	9.34	NA	0.800	NA	ZR
Hexane n-	C_6H_{14}	10.13	0.5	4.200	10	ZR
Hexene, 1-	C_6H_{12}	9.44	NA	0.900	1.2	NA
Hydrazine	H_4N_2	8.93	2.1	3.000	3	3
Hydrazoic acid	HN_3	10.72	NA	ZR	NA	NA

Appendix F (Continued)

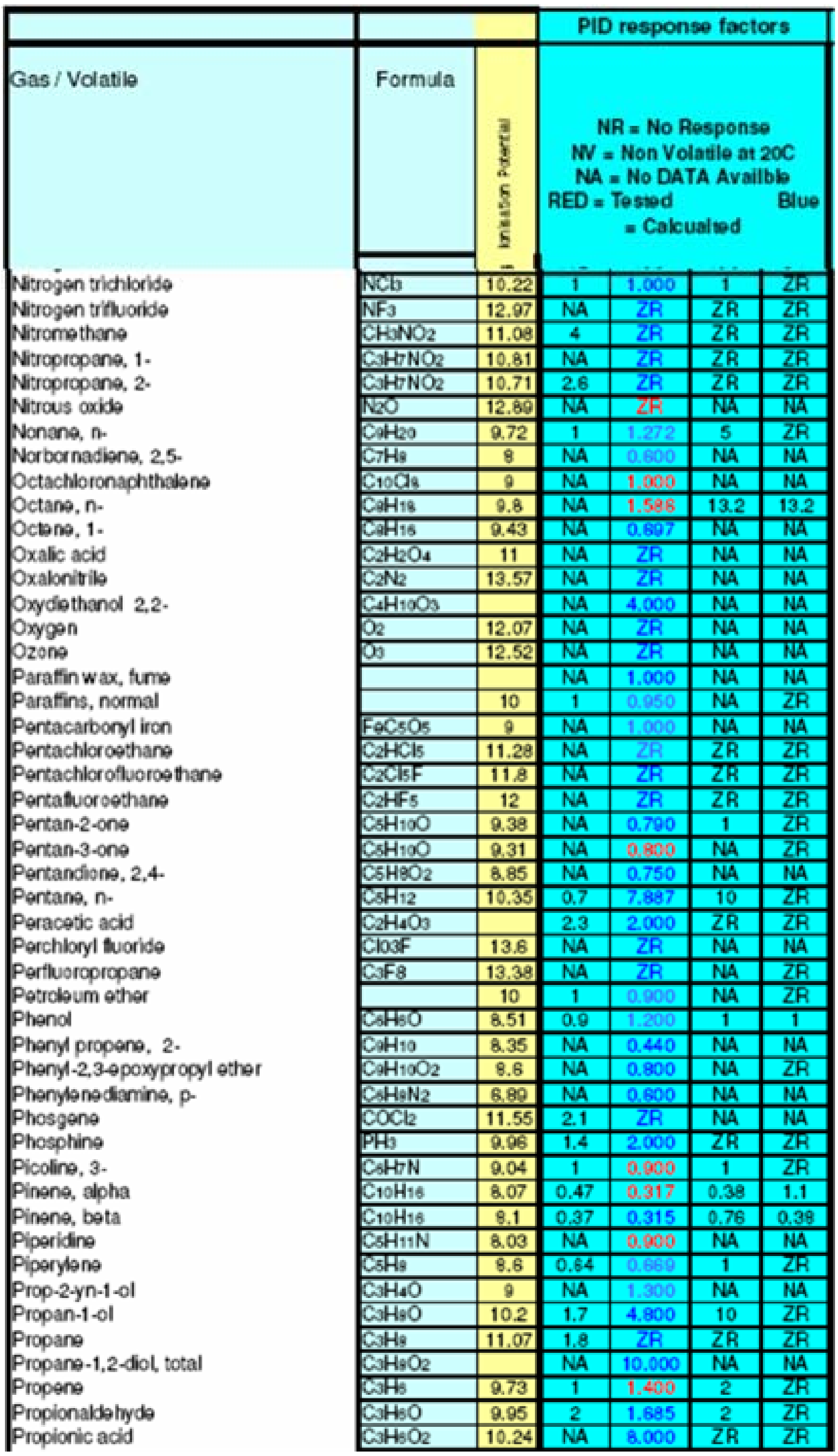


			PID response factors			
Gas / Volatile	Formula	Ionisation Potential	NR = No Response NV = Non Volatile at 20C NA = No DATA Availble RED = Tested Blue = Calcualted			
		IP	11.7	10.6	10.2	9.4
Hydrogen	H_2	15.43	ZR	ZR	ZR	ZR
Hydrogen bromide	HBr	11.62	NA	ZR	NA	NA
Hydrogen chloride	HCl	12.74	NA	ZR	NA	NA
Hydrogen cyanide	HCN	13.60	ZR	ZR	ZR	ZR
Hydrogen fluoride	HF	15.98	NA	ZR	NA	NA
Hydrogen peroxide	H_2O_2	10.54	1	4.000	ZR	ZR
Hydrogen sulfide	H_2S	10.46	1.5	4.000	ZR	ZR
Hydroquinone	$C_6H_6O_2$	7.94	NA	0.800	NA	NA
Hydroxypropyl acrylate 2-	$C_6H_{10}O_3$	9	NA	1.500	NA	ZR
Iminodi(ethylamine) 2,2-	$C_4H_{13}N_3$	9	NA	0.900	NA	ZR
Iminodiethanol 2,2'-	$C_4H_{11}NO_2$	9	NA	1.600	NA	ZR
Indene	C_9H_8	8.81	NA	0.460	NA	ZR
Iodine	I_2	9.31	0.1	0.150	1	ZR
Iodoform	CHI_3	9.25	NA	1.500	NA	NA
Iodomethane	CH_3I	9.54	0.26	0.400	1	ZR
Isoamyl acetate	$C_7H_{14}O_2$		NA	1.600	NA	NA
Isobutane	C_4H_{10}	10.57	1.2	8.000	ZR	ZR
Isobutanol	$C_4H_{10}O$	10.12	1.5	3.500	19	ZR
Isobutyl acetate	$C_6H_{12}O_2$	9.90	NA	2.260	NA	ZR
Isobutyl acrylate	$C_7H_{12}O_2$	9.50	0.6	1.300	NA	NA
Isobutylene	C_4H_8	9.24	1	1.000	2	ZR
Isobutyraldehyde	C_4H_8O	9.00	NA	1.200	NA	ZR
Isocyanates, all		10	NA	NV	NA	NA
Isodecanol	$C_{10}H_{22}O$	9.80	1	0.900	NA	ZR
Isoflurane	$C_3H_2ClF_5O$	11.00	NA	ZR	NA	NA
Isononanol	$C_9H_{20}O$	9.80	1	1.500	NA	ZR
Isooctane	C_8H_{18}	9.86	1	1.085	1	ZR
Isooctanol	$C_8H_{18}O$	9.80	1	1.700	NA	ZR
Isopentane	C_5H_{12}	10.32	4	8.000	ZR	ZR
Isophorone	$C_9H_{14}O$	9.07	NA	0.750	NA	ZR
Isoprene	C_5H_8	8.85	0.6	0.698	1	0.69
Isopropanol	C_3H_8O	10.17	2.7	4.352	40	500
Isopropyl acetate	$C_5H_{10}O_2$	9.99	NA	2.202	5	ZR
Isopropyl chloroformate	$C_4H_7O_2Cl$	10.20	NA	1.600	NA	NA
Jet Fuel JP-4		9.00	0.42	0.750	1	ZR
Jet Fuel JP-5		9.00	0.46	0.650	1	ZR
Jet Fuel JP-8		9.00	0.32	0.650	1	ZR
Kerosene		8	NA	0.830	NA	ZR
Ketene	C_2H_2O	9.617	NA	3.000	NA	ZR
Liquefied petroleum gas		10.95	NA	ZR	NA	ZR
Maleic anhydride	$C_4H_2O_3$	9.9	NA	2.000	NA	NA
Mercaptoacetic acid	$C_2H_4O_2S$	9.8	NA	1.000	NA	NA
Mercury	Hg	10.44	NA	NV	NA	NA
Mercury alkyls			NA	NV	NA	NA
Mesitylene	C_9H_{12}	8.41	0.32	0.340	0.36	1
Methacrylic acid	$C_4H_6O_2$	10.15	NA	2.300	NA	ZR
Methacrylonitrile	C_4H_5N	10.34	NA	5.000	ZR	ZR
Methane	CH_4	12.51	ZR	ZR	ZR	ZR

Appendix Figure F (Continued)

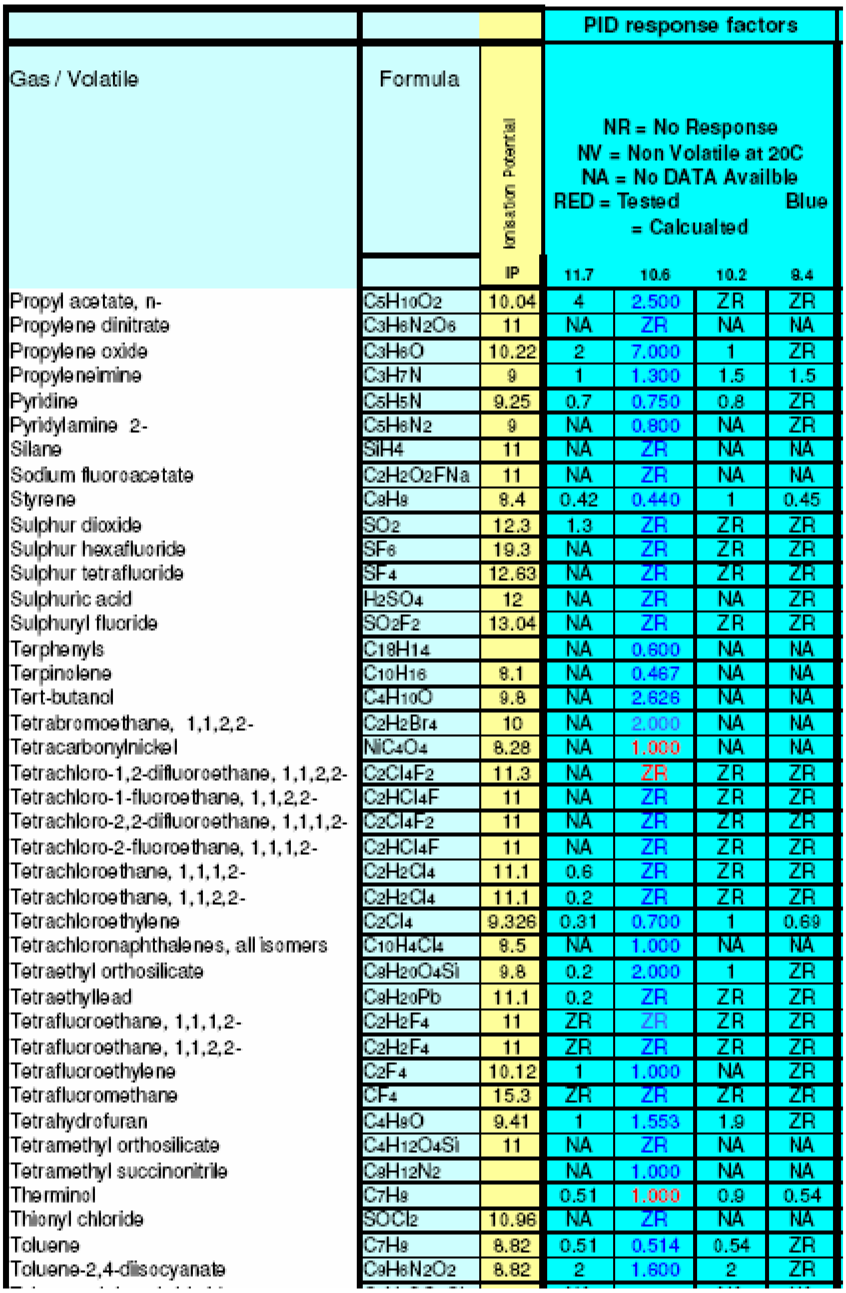
			PID response factors			
Gas / Volatile	Formula	Ionisation Potential	NR = No Response NV = Non Volatile at 20C NA = No DATA Availble RED = Tested Blue = Calcualted			
		IP	11.7	10.6	10.2	9.4
Methanol	CH_4O	10.85	2.5	200.000	ZR	ZR
Methoxyethanol, 2-	$C_3H_8O_2$	9.60	1.4	2.700	4.8	ZR
Methoxyethoxyethanol, 2-	$C_5H_{12}O_3$	10	0.9	1.400	2.3	ZR
Methoxymethylethoxy-2-propanol	$C_7H_{16}O_3$	9.3	NA	1.300	NA	ZR
Methoxypropan-2-ol	$C_4H_{10}O_2$	9.4	1.1	3.000	1.5	ZR
Methoxypropyl acetate	$C_6H_{12}O_3$	9.00	0.8	1.200	NA	ZR
Methyl acetate	$C_3H_6O_2$	10.27	1.4	5.186	1	ZR
Methyl acrylate	$C_4H_6O_2$	10.25	1.2	3.400	3	ZR
Methyl bromide	CH_3Br	10.54	1.3	1.900	ZR	ZR
Methyl cyanoacrylate	$C_5H_5O_2N$	10.00	NA	5.000	NA	NA
Methyl ethyl ketone	C_4H_8O	9.51	1.1	0.766	0.86	0.86
Methyl ethyl ketone peroxides	$C_8H_{18}O_2$		NA	0.800	NA	NA
Methyl formate	$C_2H_4O_2$	10.82	NA	ZR	ZR	ZR
Methyl isobutyl ketone	$C_6H_{12}O$	9.30	0.6	0.802	0.9	0.9
Methyl isocyanate	C_2H_3NO	10.67	1.5	ZR	ZR	ZR
Methyl isothiocyanate	C_2H_3NS	9.25	0.4	0.600	1	ZR
Methyl mercaptan	CH_4S	9.44	1	0.700	1	ZR
Methyl methacrylate	$C_5H_8O_2$	9.70	1.2	1.600	1	2.7
Methyl propyl ketone	$C_5H_{10}O$	9.39	0.79	0.790	1	ZR
Methyl salicylate	$C_8H_8O_3$	9.70	NA	1.200	NA	NA
Methyl sulphide	C_2H_6S	8.69	0.46	0.500	0.5	0.49
Methyl t-butyl ether	$C_5H_{12}O$	9.24	1	0.800	1	ZR
Methyl-2-propen-1-ol, 2-	C_4H_8O	9.60	NA	1.057	NA	NA
Methyl-2-pyrrolidinone, N-	C_5H_9NO	9.17	0.9	0.900	1	1
Methyl-4,6-dinitrophenol, 2-	$C_7H_6N_2O_5$	9.1	NA	3.000	NA	NA
Methyl-5-hepten-2-one, 6-	$C_8H_{14}O$	9.40	NA	0.800	NA	NA
Methylamine	CH_5N	8.97	1	1.400	1	ZR
Methylbutan-1-ol, 3-	$C_5H_{12}O$	9.80	NA	3.400	NA	ZR
Methylcyclohexane	C_7H_{14}	9.85	0.53	1.100	1.6	ZR
Methylcyclohexanol, 4-	$C_7H_{14}O$	9.8	NA	2.400	NA	ZR
Methylcyclohexanone 2-	$C_7H_{12}O$	9.2	NA	0.950	NA	ZR
Methylheptan-3-one, 5-	$C_8H_{16}O$	9.1	NA	0.750	NA	NA
Methylhexan-2-one, 5-	$C_7H_{14}O$	9.28	NA	0.750	NA	ZR
Methylhydrazine	CH_6N_2	8	1.3	1.300	1.4	1.4
Methyl-N-2,4, 6-tetranitroaniline, N-	$C_7H_5N_5O_8$	9	NA	3.000	NA	NA
Methylpent-3-en-2-one, 4-	$C_6H_{10}O$	9	NA	0.720	NA	ZR
Methylpentan-2-ol, 4-	$C_6H_{14}O$	9.8	NA	2.800	NA	ZR
Methylpentane-2,4-diol, 2-	$C_6H_{14}O_2$	9	NA	4.000	NA	ZR
Methylpropan-2-ol, 2-	$C_4H_{10}O$	9.70	NA	3.500	NA	ZR
Methylstyrene	C_9H_{10}	8.2	1	0.530	1	1
Mineral oil		9.00	NA	0.800	NA	NA
Mineral spirits		9.00	0.39	0.800	1	ZR
Naphthalene	$C_{10}H_8$	8.14	0.4	0.440	0.45	0.45
Nitric oxide	NO	9.27	2.8	8.000	1	ZR
Nitroaniline 4-	$C_6H_6N_2O_2$	8.85	NA	0.800	NA	NA
Nitrobenzene	$C_6H_5NO_2$	9.92	1.6	1.700	2.6	ZR
Nitroethane	$C_2H_5NO_2$	10.88	3	ZR	ZR	ZR
Nitrogen dioxide	NO_2	9.58	ZR	10.000	ZR	ZR

Appendix Figure F (Continued)



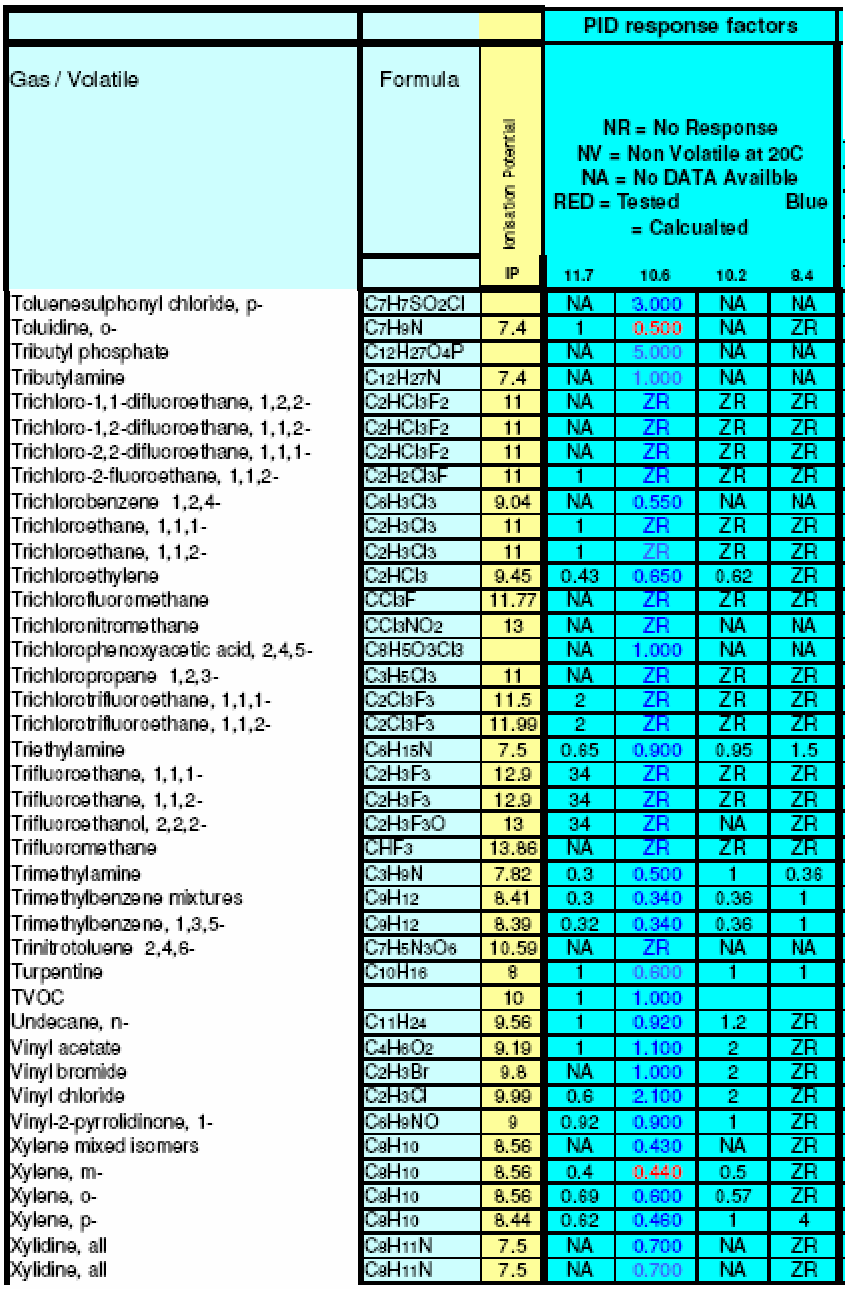
			PID response factors			
Gas / Volatile	Formula	Ionisation Potential	NR = No Response NV = Non Volatile at 20C NA = No DATA Availble RED = Tested Blue = Calcualted			
Nitrogen trichloride	NCl_3	10.22	1	1.000	1	ZR
Nitrogen trifluoride	NF_3	12.97	NA	ZR	ZR	ZR
Nitromethane	CH_3NO_2	11.08	4	ZR	ZR	ZR
Nitropropane, 1-	$C_3H_7NO_2$	10.81	NA	ZR	ZR	ZR
Nitropropane, 2-	$C_3H_7NO_2$	10.71	2.6	ZR	ZR	ZR
Nitrous oxide	N_2O	12.89	NA	ZR	NA	NA
Nonane, n-	C_9H_{20}	9.72	1	1.272	5	ZR
Norbornadiene, 2,5-	C_7H_8	8	NA	0.600	NA	NA
Octachloronaphthalene	$C_{10}Cl_8$	9	NA	1.000	NA	NA
Octane, n-	C_8H_{18}	9.8	NA	1.586	13.2	13.2
Octene, 1-	C_8H_{16}	9.43	NA	0.697	NA	NA
Oxalic acid	$C_2H_2O_4$	11	NA	ZR	NA	NA
Oxalonitrile	C_2N_2	13.57	NA	ZR	NA	NA
Oxydiethanol 2,2-	$C_4H_{10}O_3$		NA	4.000	NA	NA
Oxygen	O_2	12.07	NA	ZR	NA	NA
Ozone	O_3	12.52	NA	ZR	NA	NA
Paraffin wax, fume			NA	1.000	NA	NA
Paraffins, normal		10	1	0.950	NA	ZR
Pentacarbonyl iron	FeC_5O_5	9	NA	1.000	NA	NA
Pentachloroethane	C_2HCl_5	11.28	NA	ZR	ZR	ZR
Pentachlorofluoroethane	C_2Cl_5F	11.8	NA	ZR	ZR	ZR
Pentafluoroethane	C_2HF_5	12	NA	ZR	ZR	ZR
Pentan-2-one	$C_5H_{10}O$	9.38	NA	0.790	1	ZR
Pentan-3-one	$C_5H_{10}O$	9.31	NA	0.800	NA	ZR
Pentandione, 2,4-	$C_5H_8O_2$	8.85	NA	0.750	NA	NA
Pentane, n-	C_5H_{12}	10.35	0.7	7.887	10	ZR
Peracetic acid	$C_2H_4O_3$		2.3	2.000	ZR	ZR
Perchloryl fluoride	ClO_3F	13.6	NA	ZR	NA	NA
Perfluoropropane	C_3F_8	13.38	NA	ZR	NA	ZR
Petroleum ether		10	1	0.900	NA	ZR
Phenol	C_6H_6O	8.51	0.9	1.200	1	1
Phenyl propene, 2-	C_9H_{10}	8.35	NA	0.440	NA	NA
Phenyl-2,3-epoxypropyl ether	$C_9H_{10}O_2$	8.6	NA	0.800	NA	ZR
Phenylenediamine, p-	$C_6H_8N_2$	6.89	NA	0.600	NA	NA
Phosgene	$COCl_2$	11.55	2.1	ZR	NA	NA
Phosphine	PH_3	9.96	1.4	2.000	ZR	ZR
Picoline, 3-	C_6H_7N	9.04	1	0.900	1	ZR
Pinene, alpha	$C_{10}H_{16}$	8.07	0.47	0.317	0.38	1.1
Pinene, beta	$C_{10}H_{16}$	9.1	0.37	0.315	0.76	0.39
Piperidine	$C_5H_{11}N$	8.03	NA	0.900	NA	NA
Piperylene	C_5H_8	8.6	0.64	0.669	1	ZR
Prop-2-yn-1-ol	C_3H_4O	9	NA	1.300	NA	NA
Propan-1-ol	C_3H_8O	10.2	1.7	4.800	10	ZR
Propane	C_3H_8	11.07	1.8	ZR	ZR	ZR
Propane-1,2-diol, total	$C_3H_8O_2$		NA	10.000	NA	NA
Propene	C_3H_6	9.73	1	1.400	2	ZR
Propionaldehyde	C_3H_6O	9.95	2	1.685	2	ZR
Propionic acid	$C_3H_6O_2$	10.24	NA	8.000	ZR	ZR

Appendix Figure F (Continued)



Gas / Volatile	Formula	Ionisation Potential IP	PID response factors NR = No Response NV = Non Volatile at 20C NA = No DATA Availble RED = Tested Blue = Calcualted 11.7	10.6	10.2	9.4
Propyl acetate, n-	$C_5H_{10}O_2$	10.04	4	2.500	ZR	ZR
Propylene dinitrate	$C_3H_6N_2O_6$	11	NA	ZR	NA	NA
Propylene oxide	C_3H_6O	10.22	2	7.000	1	ZR
Propyleneimine	C_3H_7N	9	1	1.300	1.5	1.5
Pyridine	C_5H_5N	9.25	0.7	0.750	0.8	ZR
Pyridylamine 2-	$C_5H_6N_2$	9	NA	0.800	NA	ZR
Silane	SiH_4	11	NA	ZR	NA	NA
Sodium fluoroacetate	$C_2H_2O_2FNa$	11	NA	ZR	NA	NA
Styrene	C_8H_8	8.4	0.42	0.440	1	0.45
Sulphur dioxide	SO_2	12.3	1.3	ZR	ZR	ZR
Sulphur hexafluoride	SF_6	19.3	NA	ZR	ZR	ZR
Sulphur tetrafluoride	SF_4	12.63	NA	ZR	ZR	ZR
Sulphuric acid	H_2SO_4	12	NA	ZR	NA	ZR
Sulphuryl fluoride	SO_2F_2	13.04	NA	ZR	ZR	ZR
Terphenyls	$C_{18}H_{14}$		NA	0.600	NA	NA
Terpinolene	$C_{10}H_{16}$	8.1	NA	0.467	NA	NA
Tert-butanol	$C_4H_{10}O$	9.8	NA	2.626	NA	NA
Tetrabromoethane, 1,1,2,2-	$C_2H_2Br_4$	10	NA	2.000	NA	NA
Tetracarbonylnickel	NiC_4O_4	8.28	NA	1.000	NA	NA
Tetrachloro-1,2-difluoroethane, 1,1,2,2-	$C_2Cl_4F_2$	11.3	NA	ZR	ZR	ZR
Tetrachloro-1-fluoroethane, 1,1,2,2-	C_2HCl_4F	11	NA	ZR	ZR	ZR
Tetrachloro-2,2-difluoroethane, 1,1,1,2-	$C_2Cl_4F_2$	11	NA	ZR	ZR	ZR
Tetrachloro-2-fluoroethane, 1,1,1,2-	C_2HCl_4F	11	NA	ZR	ZR	ZR
Tetrachloroethane, 1,1,1,2-	$C_2H_2Cl_4$	11.1	0.6	ZR	ZR	ZR
Tetrachloroethane, 1,1,2,2-	$C_2H_2Cl_4$	11.1	0.2	ZR	ZR	ZR
Tetrachloroethylene	C_2Cl_4	9.326	0.31	0.700	1	0.69
Tetrachloronaphthalenes, all isomers	$C_{10}H_4Cl_4$	8.5	NA	1.000	NA	NA
Tetraethyl orthosilicate	$C_8H_{20}O_4Si$	9.8	0.2	2.000	1	ZR
Tetraethyllead	$C_8H_{20}Pb$	11.1	0.2	ZR	ZR	ZR
Tetrafluoroethane, 1,1,1,2-	$C_2H_2F_4$	11	ZR	ZR	ZR	ZR
Tetrafluoroethane, 1,1,2,2-	$C_2H_2F_4$	11	ZR	ZR	ZR	ZR
Tetrafluoroethylene	C_2F_4	10.12	1	1.000	NA	ZR
Tetrafluoromethane	CF_4	15.3	ZR	ZR	ZR	ZR
Tetrahydrofuran	C_4H_8O	9.41	1	1.553	1.9	ZR
Tetramethyl orthosilicate	$C_4H_{12}O_4Si$	11	NA	ZR	NA	NA
Tetramethyl succinonitrile	$C_8H_{12}N_2$		NA	1.000	NA	NA
Therminol	C_7H_8		0.51	1.000	0.9	0.54
Thionyl chloride	$SOCl_2$	10.96	NA	ZR	NA	NA
Toluene	C_7H_8	8.82	0.51	0.514	0.54	ZR
Toluene-2,4-diisocyanate	$C_9H_6N_2O_2$	8.82	2	1.600	2	ZR

Appendix Figure F (Continued)



			PID response factors			
Gas / Volatile	Formula	Ionisation Potential	NR = No Response NV = Non Volatile at 20C NA = No DATA Availble RED = Tested Blue = Calcualted			
		IP	11.7	10.6	10.2	9.4
Toluenesulphonyl chloride, p-	$C_7H_7SO_2Cl$		NA	3.000	NA	NA
Toluidine, o-	C_7H_9N	7.4	1	0.500	NA	ZR
Tributyl phosphate	$C_{12}H_{27}O_4P$		NA	5.000	NA	NA
Tributylamine	$C_{12}H_{27}N$	7.4	NA	1.000	NA	NA
Trichloro-1,1-difluoroethane, 1,2,2-	$C_2HCl_3F_2$	11	NA	ZR	ZR	ZR
Trichloro-1,2-difluoroethane, 1,1,2-	$C_2HCl_3F_2$	11	NA	ZR	ZR	ZR
Trichloro-2,2-difluoroethane, 1,1,1-	$C_2HCl_3F_2$	11	NA	ZR	ZR	ZR
Trichloro-2-fluoroethane, 1,1,2-	$C_2H_2Cl_3F$	11	1	ZR	ZR	ZR
Trichlorobenzene 1,2,4-	$C_6H_3Cl_3$	9.04	NA	0.550	NA	NA
Trichloroethane, 1,1,1-	$C_2H_3Cl_3$	11	1	ZR	ZR	ZR
Trichloroethane, 1,1,2-	$C_2H_3Cl_3$	11	1	ZR	ZR	ZR
Trichloroethylene	C_2HCl_3	9.45	0.43	0.650	0.62	ZR
Trichlorofluoromethane	CCl_3F	11.77	NA	ZR	ZR	ZR
Trichloronitromethane	CCl_3NO_2	13	NA	ZR	NA	NA
Trichlorophenoxyacetic acid, 2,4,5-	$C_8H_5O_3Cl_3$		NA	1.000	NA	NA
Trichloropropane 1,2,3-	$C_3H_5Cl_3$	11	NA	ZR	ZR	ZR
Trichlorotrifluoroethane, 1,1,1-	$C_2Cl_3F_3$	11.5	2	ZR	ZR	ZR
Trichlorotrifluoroethane, 1,1,2-	$C_2Cl_3F_3$	11.99	2	ZR	ZR	ZR
Triethylamine	$C_6H_{15}N$	7.5	0.65	0.900	0.95	1.5
Trifluoroethane, 1,1,1-	$C_2H_3F_3$	12.9	34	ZR	ZR	ZR
Trifluoroethane, 1,1,2-	$C_2H_3F_3$	12.9	34	ZR	ZR	ZR
Trifluoroethanol, 2,2,2-	$C_2H_3F_3O$	13	34	ZR	NA	ZR
Trifluoromethane	CHF_3	13.86	NA	ZR	ZR	ZR
Trimethylamine	C_3H_9N	7.82	0.3	0.500	1	0.36
Trimethylbenzene mixtures	C_9H_{12}	8.41	0.3	0.340	0.36	1
Trimethylbenzene, 1,3,5-	C_9H_{12}	8.39	0.32	0.340	0.36	1
Trinitrotoluene 2,4,6-	$C_7H_5N_3O_6$	10.59	NA	ZR	NA	NA
Turpentine	$C_{10}H_{16}$	8	1	0.600	1	1
TVOC		10	1	1.000		
Undecane, n-	$C_{11}H_{24}$	9.56	1	0.920	1.2	ZR
Vinyl acetate	$C_4H_6O_2$	9.19	1	1.100	2	ZR
Vinyl bromide	C_2H_3Br	9.8	NA	1.000	2	ZR
Vinyl chloride	C_2H_3Cl	9.99	0.6	2.100	2	ZR
Vinyl-2-pyrrolidinone, 1-	C_6H_9NO	9	0.92	0.900	1	ZR
Xylene mixed isomers	C_9H_{10}	8.56	NA	0.430	NA	ZR
Xylene, m-	C_9H_{10}	8.56	0.4	0.440	0.5	ZR
Xylene, o-	C_9H_{10}	8.56	0.69	0.600	0.57	ZR
Xylene, p-	C_9H_{10}	8.44	0.62	0.460	1	4
Xylidine, all	$C_9H_{11}N$	7.5	NA	0.700	NA	ZR
Xylidine, all	$C_9H_{11}N$	7.5	NA	0.700	NA	ZR

Appendix Figure F (Continued)

Appendix G

Pictures of the experiment

Appendix figure G1 Wastewater sludge used in the experiment

Appendix figure G2 Compaction of the material after the experiment finished

CIRRICULUM VITAE

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