



# **ASSESSMENT OF SOIL QUALITY AND DIOXIN CONTAMINATION AT BIEN HOA AIRBASE, VIETNAM**

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## **ABSTRACT**

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Bien Hoa Airbase was the largest dioxin contamination hotspot in Vietnam. Dioxin contamination has caused serious environmental and health problems so different dioxin remediation projects has been carried out there.

The purpose of this study was to assess the soil quality and the differences in physical-chemical properties of dioxin contaminated soils and non-contaminated soils at Bien Hoa Airbase. Another purpose was to assess different remediation technologies on environmental compatibility basis and suggest environmentally friendly technologies adapting to the soil conditions at Bien Hoa Airbase.

The dioxin concentration in soil were measured and the soil quality was assessed by conducting the following analysis: particle-size distribution, wet aggregate stability, pH, redox potential, electrical conductivity and total organic carbon. All experiments were carried out in the laboratory. The assessment of remediation technology was based on the Environmental Assessment report of Bien Hoa Airbase and other literatures.

The results showed that dioxin concentration in the majority of samples taken from Pacer Ivy area exceeded allowed limits. Dioxin contaminated soil had higher clay content than normal soil. Soil structure at all locations was very poor, characterized by low organic matter content and low wet aggregate stability. Regarding to remediation technologies, thermal treatment which was selected for some remediation project in Vietnam might cause harms to the environment. Further findings indicated that combination of phytoremediation using vetiver grass and bioremediation using anaerobic microorganisms was a more environmentally friendly alternative for dioxin contamination at Bien Hoa Airbase.

More research on this combined remediation method should be done to determine the effectiveness and the practicability of the treatment. In addition, future study on the soil quality at Bien Hoa Airbase can be improved with some modifications in the methodology.

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Key words: dioxin, dioxin contamination in soil, soil quality, dioxin contaminated soil remediation

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## ABBREVIATIONS AND TERMS

EA	Environmental Assessment
EC	Electrical Conductivity
GVN	Government of Vietnam
ISTD	<i>In situ</i> Thermal Desorption
IPTD	<i>In pile</i> Thermal Desorption
MND	Ministry of National Defence
ORP	Oxidation Reduction Potential
PEER	Partnerships for Enhanced Engagement in Research
PCDD	Polychlorinated dibenzo- <i>p</i> -dioxin
PCDF	Polychlorinated dibenzofuran
TCDD	2,3,7,8-tetrachlorodibenzo- <i>p</i> -dioxin
TCH	Thermal Conduction Heating
TEF	Toxic Equivalency Factor
TEQ	Toxic Equivalent
TOC	Total Organic Carbon
US	The United States of America
USAID	United States Agency for International Development
WHO	World Health Organization

## 1 INTRODUCTION

During the Vietnam – US war, US forces started a mission in 1962 named Operation Ranch Hand, aiming to defoliate forests and destroy crops by spraying over 80 million litres of herbicides, of which 50 million litres was Agent Orange. Agent Orange and some other herbicides used contained toxic chemicals polychlorinated dibenzo-*p*-dioxins (PCDDs), especially the most toxic congener 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD), and polychlorinated dibenzofurans (PCDFs). All of them are commonly known as dioxins. The mission ended in 1971 with Pacer Ivy mission, which was launched to re-drum and ship all remaining herbicides to Johnston Atoll in Pacific Ocean. (Institute of Medicine, 1994). Although nearly 50 years have passed, residual dioxin still exist in soils, sediments, and other mediums at high concentration in several areas, causing serious environmental and human health problems. Bien Hoa Airbase was the most active and largest Ranch Hand sites. The storing, handling and spilling of Agent Orange there was the reason for dioxin contamination in the soil. (USAID, 2016).

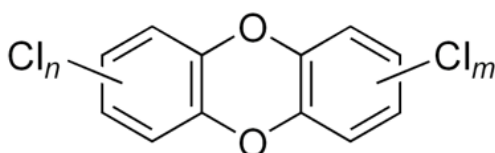
The Government of Vietnam and the US have put a joint effort to diminish the dioxin contamination at the site. A dioxin remediation project has been successfully launched at Da Nang Airport, one of the major dioxin hotspots and several projects have been launched at Bien Hoa Airbase. Thermal treatment technologies were selected as primary dioxin contamination treatment methods for these projects (USAID, 2016). From an environmental point of view, the construction and implementation of thermal degradation system may cause negative effects on the environment and alter soil properties. However, selection of these technologies often focuses on their performance to diminish the contamination but not their effects on soil. (Vidonish et al., 2016).

Assessment of soil properties will provide knowledge on the soil current quality and the fate of dioxins in soil. Understanding dioxin behaviours and soil characteristics will help determine suitable environmentally friendly alternatives or ecosystem restoration plan. This thesis was done as a part of USAID funded research project *Field-scale Application of Vetiver Grass to Mitigate Dioxin Contaminated Soil at Bien Hoa Airbase, Vietnam*.

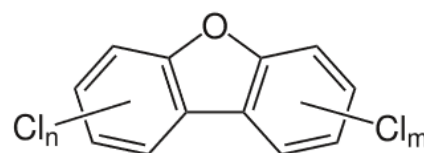
## 1.1 Background information of dioxin

### 1.1.1 Physical, chemical properties and environmental behaviour in soils

Polychlorinated dibenzo-*p*-dioxins (PCDDs) with 75 congeners and polychlorinated dibenzofurans (PCDFs) with 135 congeners are two families of planar, tricyclic aromatic compounds. Only 17 isomers, which have chlorine groups attached to positions 2, 3, 7 and 8 on the benzene rings are considered highly toxic for humans and animals. (Fiedler, 2003, pp. 126–127 ).



General structure of  
polychlorinated dibenzo-*p*-dioxins



General structure of  
polychlorinated dibenzofurans

FIGURE 1. General structure of PCDDs/PCDFs (Edgar191, 2008; Leyo, 2009)

The fate in the soils of PCDD/PCDFs is governed by a number of physical and chemical properties. Dioxins have very low water solubility (from 0,074 ng/L to 419 ng/L for 17 most toxic congeners), and normally low Henry's law constant, so they will resist against water and will not mobilized in soils by rainfall. Being superhydrophobic and highly lipophilic substances with sorption partition coefficient  $K_{oc}$  ranging between 6,4 and 7,6, PCDD/PCDFs tend to adsorb onto organic matter in soils and sediments. (AEA Technology, 1999, pp. 5–6; Fiedler, 2003, pp. 127–129). Consequently, their mobility in soil maybe trivial. Meanwhile, it is important to also consider environmental factors such as clay content, pH, moisture and organic matter. (AEA Technology, 1999, pp. 15–16).

Dioxins appear in soils through numerous ways, commonly wet and dry deposition from the atmosphere, penetration of water containing contaminated sediments, spills of chemicals containing trace of dioxins and application of sewage sludge (AEA Technology, 1999, pp. 12–13). The main source of dioxins in recent

years is from the municipal solid waste incineration. Besides, dioxins can be introduced into the environment by sewage sludge, chlorine production (primary source in the past) and nature sources such as forest fires, volcano eruptions and biological formation from chlorinated phenols. (Fiedler, 2003, pp. 165–173).

Dioxins are persistent in soils, the more chlorine atoms attached, the more persistent the congeners. There are variations in dioxin's half life, due to different half life models. (AEA Technology, 1999, p. 14). The average half life of a dioxin congener can be in between 2 – 10 years (Mackay, Shiu, Ma, & Lee, 2006). Dioxins may degrade in soil through a number of mechanisms, reportedly volatilization, photodegradation, microbial degradation and biodegradation (AEA Technology, 1999, pp. 14-16; Urbaniak, 2013). Depending on the congeners, the depth of dioxins in soil layers and environmental conditions such as temperature and soil properties like pH, ORP, water content and organic carbon content, the rate of dioxin degradation can vary moderately. For example, dioxin presented in the topsoil layer (at around 1 cm depth), volatilize quickly in summer months, but dioxins in sublayer (below 5 cm) can take years to degrade or chlorinated isomers basically do not volatilize under most environmental conditions. (AEA Technology, 1999, pp. 14–16).

### **1.1.2 Toxicity**

The 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD) is the most toxic isomer amongst 210 dioxin isomers. Thus, most studies on dioxin toxicity focus on the toxic effects on human of this compound. Exposures to dioxins can cause severe damage to immune system and some regulatory systems. However, due to the lack of available data on other congeners than 2,3,7,8-TCDD, only 2,3,7,8-TCDD is classified as carcinogen by International Agency for Research on Cancer (IARC). In addition to cancer risks, it was reported that dioxins caused anomaly change in the sex ratio, chronic diseases such as diabetes and neurological diseases in children exposed to dioxins in mother's womb. (Fiedler, 2003, pp. 145–150).



In order to regulate PCDDs/PCDFs, WHO has developed a set of toxicity equivalent values for the most dangerous dioxin and dioxin-like compounds, expressed as Toxic Equivalency Factors (TEF). 2,3,7,8-TCDD, being the most toxic congener, has the highest TEF of 1. Since then, the toxicity of dioxins has been reported in a single value toxic equivalent TEQ, which is determined based on TEF. (Fiedler, 2003). The table below presents the most recent WHO TEF for 17 chlorinated dioxin congeners.

TABLE 1. WHO 2005 TEF values for chlorinated dioxin compounds (Berg et al., 2006)

Compound	WHO 2005 TEF
Chlorinated dibenzo- <i>p</i> -dioxins	
2,3,7,8-TCDD	1
1,2,3,7,8-PeCDD	1
1,2,3,4,7,8-HxCDD	0,1
1,2,3,6,7,8-HxCDD	0,1
1,2,3,7,8,9-HxCDD	0,1
1,2,3,4,6,7,8-HpCDD	0,01
OCDD	0,0003
Chlorinated dibenzofurans	
2,3,7,8-TCDF	0,1
1,2,3,7,8-PeCDF	0,03
2,3,4,7,8-PeCDF	0,3
1,2,3,4,7,8-HxCDF	0,1
1,2,3,6,7,8-HxCDF	0,1
2,3,4,6,7,8-HxCDF	0,1
1,2,3,7,8,9-HxCDF	0,1
1,2,3,4,6,7,8-HpCDF	0,01
1,2,3,4,7,8,9-HpCDF	0,01
OCDF	0,0003

### 1.1.3 Overview of remediation methods for dioxin contamination in soil

A soil remediation method is decided by a dioxin degradation mechanism, such as volatilization, microbial degradation or biodegradation. The applicability of a technology for treatment of dioxin contaminated soil is based on a set of criteria consisting of effectiveness, implementability, cost and environmental impacts. (USAID, 2016, pp. 104–107). However, this section is dedicated to briefly summarize and review a number of remedial methods focusing on the environmental

consequences. These technologies can be divided into 3 categories: thermal treatment, biological treatment and phytoremediation.

### **Thermal treatment**

Current treatment technologies which are potentially applicable or successfully applied for treatment of dioxin contaminated soil are thermal treatment methods such as incineration and *ex situ* thermal conduction heating. Rotary kiln incineration is the most popular incineration technology in the US and is one of three treatment alternatives proposed to completely treat soil and sediment above dioxin limits set by Government of Vietnam (GVN) at Bien Hoa Airbase. (USAID, 2016, pp. 103–104, 129). Contaminated soil will be burnt in the rotary kiln incinerator at a temperature around 900-1600°C a few times in a residence time of 40 – 60 minutes so all organic materials including dioxins will be completely destroyed. In addition to treated soils, ash and gases produced in the combustion process are also discharged from the incinerator. While the ash exits directly from the incinerator, flue gases are treated and monitored before released into the environment to prevent air pollution. (USAID, 2016, p. 131; U.S. Congress, Office of Technology Assessment, 1991, p. 16). Significant environmental impacts concerning surface water quality, air quality and GHGs are associated with this technology, mainly because of the construction activities, the handling of the soil and the incineration process. These impacts are assessed as Mitigable with implemented mitigation measures in the EA of Bien Hoa Airbase, but incineration did not pass the screening for applicable technologies for dioxin treatment at Danang Airport on account of public concern about air pollution potential (USAID, 2010, p. 5-2, 2016, pp. 135–136).

*In situ/In pile* thermal desorption (ISTD/IPTD), an example of *ex situ* TCH technology, was successfully applied for the remediation project in Da Nang Airport, thus it is also considered as one of the treatment alternatives in the Bien Hoa Airbase's EA. Dioxin contaminated soil will be transported to a pile structure to undergo several stages of heating, boiling and drying to reach a temperature of minimum 335°C for approximately 21 days. This process allows dioxin to destruct with different mechanisms, specifically volatilization then either oxidation or py-

rolysis and hydrolysis or hydrous pyrolysis when in aqueous phase. A small percentage of undegraded dioxin is recovered through heated vapor extraction wells. (USAID, 2010, pp. 5-35–5-36, 2016, pp. 138–139). *Ex situ* TCH will also cause similar environmental problems as incineration technology, mostly in construction and operation phase (USAID, 2016, p. 144). However, unlike incineration, there was no concern about the pollutants in flue gas, which contributed to the decision of choosing ISTD/IPTD for treatment of dioxin contamination at Da Nang Airport (USAID, 2010, p. 5-2).

### **Biological treatment**

Bioremediation technology, which utilizes microorganisms to transform dioxins into less toxic substances, was retained after initial screening for a remedial technology in both EAs of Bien Hoa Airbase and Da Nang Airport when incorporated with landfill method. This technology was called Active Landfill but is was considered as a containment alternative instead of treatment alternative due to the fact that its effectiveness for treatment was unknown. Previous studies show no prove of biodegradation treating dioxins below GVN standards or successfully implemented on other than lab scale. (USAID, 2016, pp. 113–114).

In biological remediation, microorganisms use dioxins as carbon and energy source. Dioxin can be degraded by aerobic or anaerobic transformation. Aerobic biodegradation occurs in environment with presence of oxygen. In most of the cases, aerobic microorganisms require another carbon source in addition to PCDDs/PCDFs. Different studies reported that aerobic microorganisms only effectively destroy monochlorinated dioxins or dioxins with less than 5 chlorine atoms. (Urbaniak, 2013, p. 78; USAID, 2010, p. 5-26). On the contrary, anaerobic microorganisms perform better in transforming more chlorinated PCDDs/PCDFs by using PCDDs/PCDFs as electron acceptors in environment lack of oxygen for reductive dichlorination process (Urbaniak, 2013, pp. 79–80).

While active landfill does not have intensive energy requirement like thermal treatment methods, it poses long-term environmental risks as a result of the requirements for long-term operation and maintenance and the need of clean fill for backfill excavations after the removal of contaminated soil. The construction of

landfill also has potential negative effects on surface water quality, air quality and GHGs. The EA report of Da Nang Airport even ranked active landfill as having the higher potential environmental impact than ISTD/IPTD (USAID, 2010, p. 8-4).

## **Phytoremediation treatment**

Phytoremediation treatment method involves the use of green plants to remove, break down or stabilize contaminants in the environment. Treatment of contaminated soil is accomplished via different biochemical/physical processes in plants. For example, plants can adapt contaminants into less toxic form, isolate and store pollutants, adsorb pollutants or remediate contaminants by interacting with microorganisms in the rhizosphere. (Strandberg, Odén, Nieto & Björk, 2011).

Until now, phytoremediation technologies are relatively new. Only a few studies demonstrated dioxin treatment using plants, and most of them were on small scales. (Urbaniak, 2013). Hence, unlike the two treatments summarized above, phytoremediation was not listed as a potential technology for treatment of dioxin contamination in soil in any of the EA for dioxin hotspots in Vietnam. However, a project for field-scale application of phytoremediation for dioxin contamination using Vetiver grass is ongoing at Bien Hoa Airbase. (USAID, 2016, p. 162). Although an evaluation for potential environmental impacts of this technology is not available, phytoremediation is known as an environmentally friendly alternative for physical or physical-chemical treatment (Urbaniak, 2013).

## **1.2 Background information of study area**

### **1.2.1 Overview of Bien Hoa Airbase**

Bien Hoa Airbase is a military airbase, located in Bien Hoa City, Dong Nai province, around 30 km to the northeast of Ho Chi Minh City. The 1000-ha airbase lies on low-land, surrounded by dense residential area and next to Dong Nai river. Little information on soil properties is covered in previous assessments of Bien Hoa Airbase. An Environmental Assessment (EA) conducted in 2014/2015 found

that the composition of the soils was mainly sand, a relatively equal amount of silt and clay and gravel occupied the smallest part. Bien Hoa's climate is divided into two seasons, dry season (November to April) and rainy season (May to October). In raining season, the average monthly precipitation is around 200 mm. Regardless of the season, the monthly temperature in Bien Hoa always fluctuates within 22-36°C. (USAID, 2016, pp. 222–224).

Parts of the airbase including a few ponds have been used for agriculture and aquaculture activities such as raising cattle and poultry, harvesting fish and other aquatic products. In 2010, a fishing ban has been issued by the Airbase management boards, though these activities were still observed in during an assessment process in 2015. In an airbase development plan by the Vietnam Ministry of National Defence (MND), the land use will include both industrial and urban residential purpose, depending on the areas. This will also correspond with GVN limits for dioxin that will be mentioned in the discussion. (USAID, 2016, pp. 51, 71).

### **1.2.2 Dioxin contamination on Bien Hoa Airbase and its vicinity**

Dioxin was an unwanted by-product originated in herbicides (mostly Agent Orange) that were sprayed in Vietnam to defoliate jungles and crops in a mission called Operation Ranch Hand (1962-1971) during the US-Vietnam war. Bien Hoa Airbase was the most active site of the mission, where over 16 million litres of Agent Orange were stored and handled. During this period, especially before 1971 when mission Pacer Ivy was launched to gather and barrel all remaining herbicides to ship to the Pacific Ocean, several spills occurred, releasing approximately 25000 litres of Agent Orange into the environment. As a result, poor storage condition and these spills has turned Bien Hoa into a dioxin hotspot. (USAID, 2016, p. 52; Young et al., 2004).

In the Environmental Assessment program, the airbase was divided into nine sampling areas and smaller decision units: ZI Area, ZT Area, Southwest Area, Pacer Ivy Area, Northwest Area, Northern Forest Area, Northeast Area and Areas Outside the Airbase. This thesis focus on the Pacer Ivy Area, which is located on

the northwest of the Airbase, next to the left of the current runway, where Agent Orange was stored and redrummed during the Pacer Ivy mission and the Southwest Area, located on the southwest of the airbase, contiguous to residential area. Although the Southwest Area was suspected as a storage location for the herbicide as high concentration of dioxins was observed here, the sampling area chosen in this study was away from the suspected contamination site and had insignificant amount of dioxin in its soils. (USAID, 2016, pp. 56–60). Thus, the samples taken from this area were used as non-contaminated samples for comparison with dioxin contaminated soils. Previous studies on these areas disclosed the TCDD concentration of the Pacer Ivy Area ranged between 0,118 and 962559 ppt TEQ based on a total of 150 samples from 4 different researches, of which 80 samples exceed GVN Dioxin Standards (QCVN 45:2012/BTNMT). Only two studies with 24 soil samples collected from the Southwest Area was conducted, recording the TCDD concentration in between 4,12 and 65500 ppt TEQ, nearly 20% of the samples exceeded the standards.

## 2 AIMS AND SCOPE

The main aim of this thesis was to assess the soil quality at Bien Hoa Airbase and the differences in physical-chemical properties of dioxin contaminated soils and non-contaminated soils. The secondary aim was to assess the environmental compatibility of treatment technologies for dioxin contaminated soil and recommend an environmentally benign dioxin contamination remediation suitable for the soil condition at Bien Hoa Airbase.

This thesis was done as a part of project *Field-scale Application of Vetiver Grass to Mitigate Dioxin Contaminated Soil at Bien Hoa Airbase, Vietnam* supported by USAID through PEER Cycle 6 program (AID-OAA-A-11-00012; 2018-2020). Only the following soil quality properties were evaluated in this study: particle-size distribution, wet aggregate stability, pH, redox potential, electrical conductivity, and total organic carbon. These parameters were chosen as they were relevant to the main project. The recommendations for dioxin treatment technology were established on environmental consequences of soil quality assessment results and both remediation process and post-remediation.

### 3 METHODS

#### 3.1 Sampling

The research was conducted in Bien Hoa Airbase. Two different study areas were chosen, one was located North West of the Bien Hoa Airbase and the other was in the South West. The North West location was in the Pacer Ivy area, where high concentration of dioxin and furan were recorded. The South West location was non-contaminated area. Each area was divided into 6 plots of 10\*10 m. The exact locations were recorded using a GPS device and shown in Figure 2 and 3.

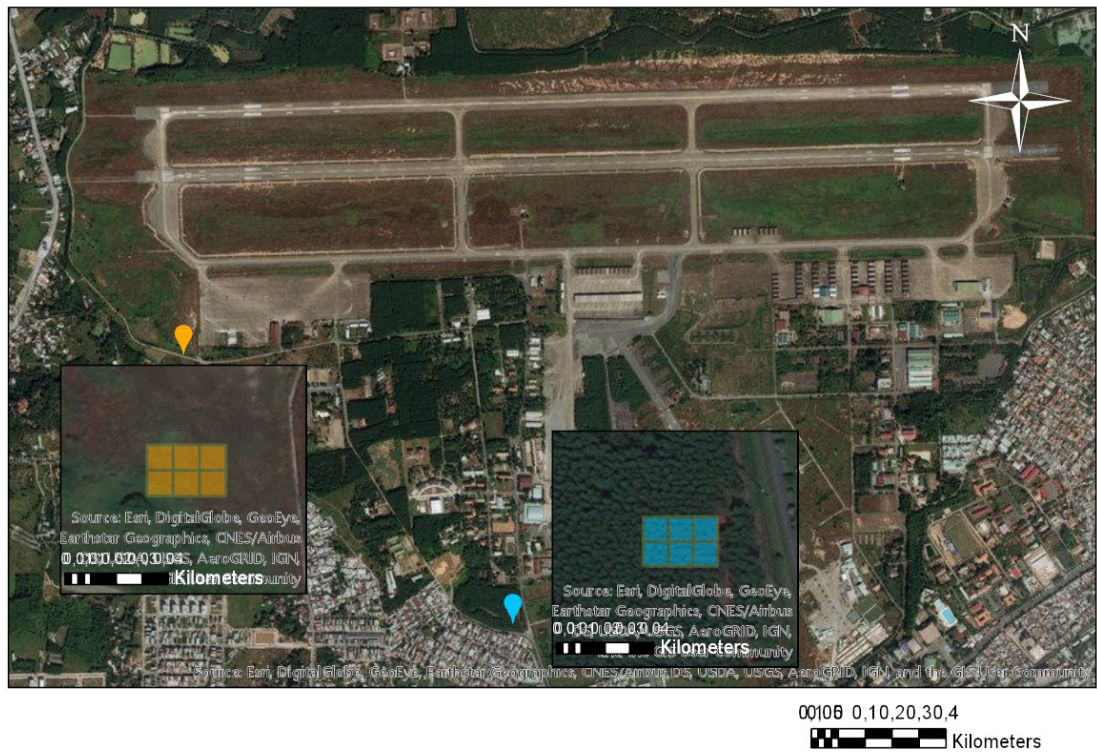


FIGURE 2. Study area



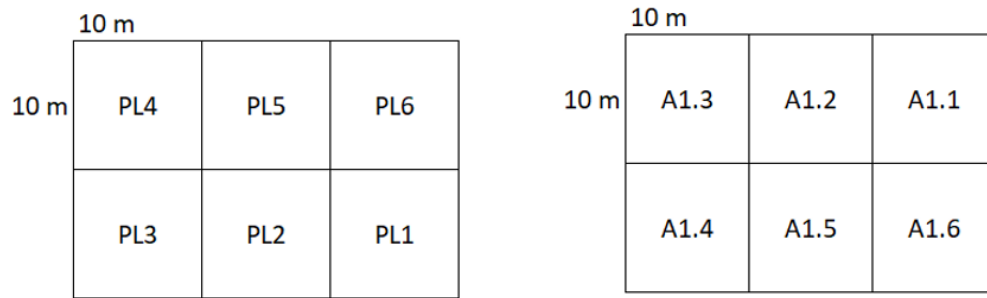


FIGURE 3. Configuration of sample plot in each study area

Due to the feature of the soil in each area and the nature of the mother project, the dioxin contaminated samples and the normal samples were collected using Edelman combination auger in different approaches. Dioxin contaminated samples were taken in October 2018 at 60 cm deep, and 30 subsamples from each plot were mixed into a representative sample. The sampling in 2018 were conducted by members from the “*vetiver*” project. Normal samples were taken in February 2019, and each sample was a blend of 5 subsamples from 5 different boreholes in a plot. Because the ground was very hard, drilling was done with help of soldiers at Bien Hoa Airbase, then normal subsamples were collected and mixed by the thesis’ author. The depth of these boreholes was only 30 cm. Sampling was not carried out at plot A1.3 due to a difficulty in drilling and time constraint. Although it was expected that these differences would not considerably affect the comparability of two sample groups, factors such as climate and soil layer depth that possibly affects the outcome of this study will be discussed later.

### 3.2 Dioxins analysis

The concentration of dioxins and furans (PCDDs/PCDFs) for dioxin contaminated soil samples and normal soil samples were analysed by Centre for Environmental Monitoring and Vietnam-Russia Tropical Centre, respectively. The method used for the determination of dioxins in the samples was U.S. EPA Method 1613B. The concentration of PCDDs/PCDFs was reported in Toxic Equivalent (TEQ), which was calculated as follows:

$$TEQ = \sum (TEF \times C) \quad (1)$$

In which:

TEQ is Toxic Equivalent (ng/kg)

TEF is Toxic Equivalency Factor

C is the mass concentration of the toxic chemical (ng/kg)

### **3.3 Physical properties**

#### **3.3.1 Particle size distribution**

The particle size distribution analysis was conducted according to modified methods based on Vietnam Standard on Soils – Laboratory methods for particle – size analysis TCVN 4198:2014 (Vietnam Institute for Building Science and Technology, 2014). All calculations were processed in a programmed Excel template. The soil samples were dried in the oven at 105 °C to constant weight. Approximately 100 g of each soil sample was weighed and passed through a 0,5 mm sieve, stones and roots larger than 0,5 mm were separated out. The soil > 0,5 mm was soaked in water in 1 hour for wet sieving method. 30-40g of the soil < 0,5 mm was accurately weighed for wet sieving and analysis by hydrometer. Dry sieving method was also performed in conjunction with wet sieving process.

##### **3.3.3.1 Wet sieving**

After soaked in water, organic matter such as roots floated on the surface of water so they could be easily removed. Soil samples were sieved through 0,25 mm sieve under running water. The soil remained on the sieve was dried in the oven at 105 °C until the weight of each soil sample unchanged. After drying, each sample was dry sieved to pass through a set of sieves 10 mm, 5 mm, 2 mm and 1 mm. Weight of the soil remaining on each sieve and the soil passing through 1 mm sieved were weighed.

The percentage of a particle size group remained on a sieve was determined:

$$P_i = \frac{m_i}{m_0} \times 100 \quad (2)$$

In which

$P_i$  is percentage of soil retained on sieve  $i$  (%)

$m_0$  is weight of soil sample (g)

$m_i$  is weight of soil retained on sieve  $i$  (g)

The cumulative percentage of soil of soil passed through a sieve was then calculated using the equation below:

$$P_{\text{cumulative } i} = 100 - \sum_{i-1}^{\text{top sieve}} p_i \quad (3)$$

In which

$P_{\text{cumulative } i}$  is cumulative percentage of particle passed through sieve  $i$  (%)

$\sum_{i-1}^{\text{top sieve}} p_i$  is total percentage of soil retained on top sieve to sieve  $i$  (%)

The results were presented as tables and semi log graphs.



FIGURE 4. Dry sieving

### 3.3.3.2 Hydrometer test

The weighed soil that passed through 0,5 mm sieve of each sample was placed in an Erlenmeyer flask with 200 ml of water and let stand overnight. 3 ml of deflocculating agent sodium hexametaphosphate ( $\text{NaPO}_3$ )<sub>6</sub> was added into the mixture then the mixture was boiled gently in 20 minutes and left until cool to room temperature. After that, they were sieved through 0,1 mm sieve. Soil passed through 0,1 mm sieve was collected in a cylinder and soil remained on the sieve was oven dried. Oven dried soil was then passed through 0,25 mm sieve. Both soil on top of the sieve and soil passing through sieve were weighted.

The cumulative percentage of particle group on 0,25 mm and 0,1 mm sieve was calculated using the following formula:

$$P = \frac{m_h}{m} (100 - K) \quad (4)$$

In which:

$m_h$  is dry weight of particles on 0,25 mm and 0,1 mm sieve (g)

$m$  is dry weight of soil sample used for hydrometer test (g)

$K$  is total percentage of particles on 0,5 mm and larger sieves (%)

The hydrometer was calibrated, and meniscus correction was determined. The cylinder was made up to 1 L with water. A hand stirrer was used to mix the mixture up and down. The mixture was allowed to stand, and the time was noted. After ½, 1, 2, 15, 30 and 60 minutes, the hydrometer readings were recorded.



FIGURE 5. Hydrometer test

First, the diameter of soil particle at different settling times was determined based on the formula below:

$$d = \sqrt{\frac{1800 \times \eta}{g(\rho_s - \rho_n)}} \times \frac{L}{t} \quad (5)$$

In which

$d$  is relative diameter of soil particle (mm)

$\eta$  is dynamic viscosity of water at experiment temperature, referred from Appendix B of TCVN4198:2014 (Poise)

$g$  is gravitational acceleration, which is  $981 \text{ cm/s}^2$

$\rho_s$  is soil particle density ( $\text{g/cm}^3$ )

$\rho_n$  is water density, which is  $1 \text{ g/cm}^3$

$t$  is the settling time of soil particle from after mixing and until reading taken(s)

$L$  is effective length for the hydrometer reading, based on Appendix A of TCVN 4198:2014 (cm)

Next, the cumulative percentage of particle smaller than diameter  $d$  which corresponded to hydrometer reading and diameter  $d$  was calculated as follows:

$$P_{\text{cumulative}} = \frac{\rho_s}{(\rho_s - 1)} \times \frac{R'_B}{m} (100 - K) \quad (6)$$

In which

$R'_B$  is corrected hydrometer reading, which was calculated using the following formula:

$$R'_B = R_B + m_B + n_B - C_B \quad (7)$$

$R_B$  is hydrometer type B reading

$m_B$  is temperature correction coefficient for hydrometer type B, based on Table B.2 (TCVN 4198:2014)

$n_B$  is meniscus correction coefficient for hydrometer type B

$C_B$  is deflocculating agent correction coefficient matching experiment using hydrometer type B

### 3.3.2 Soil density

Density of the soil was determined by pycnometer according to Viet Nam Standard on Soil Quality - Method of determining particle density and porosity TCVN 11399:2016 (Soils and Fertilizers Research Institute, 2016). First, 10-15 g of each soil sample was weighed accurately and carefully added to a pycnometer. The pycnometer was then filled half full with distilled water and boiled at 300 °C in 20 minutes. The pycnometers were cooled down to room temperature. After cooled down, the pycnometer was filled with distilled water and a stopper was inserted carefully to let the excess air and water escape through the hole on the stopper. The pycnometer was dried and cleaned before weighed. After weighing, the stopper was removed, and a thermometer was inserted to measure the temperature.

The soil and water in the pycnometer were removed and cleaned thoroughly. Then, the pycnometer was filled with distilled water only and sealed with the stopper to remove excess water. The weight of the pycnometer and the water were recorded. The soil density was calculated according to the following formula:

$$d = \frac{D \times p}{p + p_1 - p_2} \quad (8)$$

In which:

D is density of water (g/cm<sup>3</sup>)

p is weight of soil sample (g)

p<sub>1</sub> is weight of pycnometer containing water (g)

p<sub>2</sub> is weight of pycnometer containing water and soil (g)

### 3.3.3 Wet Aggregate Stability (WAS)

The analysis method was adapted from a study by Daragmeh, Jensen and Petersen (2009). Approximately 30 g of oven-dried soil was passed through 2 mm and 1 mm sieves and 1-2 mm soil was weighed. The soil was soaked in water for wet sieving on 0,25 mm sieve and dried in oven to constant weight. The soil was weighed again, this is the weight of soil remained on the sieve.

Next, the sand content of the soil was determined. 200 ml of water and 3 ml of deflocculating agent sodium hexametaphosphate (NaPO<sub>3</sub>)<sub>6</sub> was added into the soil in an Erlenmeyer flask. The mixture was boiled gently in 20 minutes and let cooled down completely. After that, the mixture was rinsed under running water and sieved with 0,25 mm sieve. The soil was dried in the oven at 105 °C over night until the weight was constant. The weight of this soil was the weight of sand.

Finally, the WAS was calculated using the formula below:

$$WAS = \frac{(m_1 - m_2)}{(m_0 - m_2)} \times 100 \quad (9)$$

In which

m<sub>0</sub> is weight of soil sample (g)

m<sub>1</sub> is weight of soil retained on the sieve (g)

m<sub>2</sub> is weight of sand (g)

## 3.4 Chemical properties

### 3.4.1 pH, Electrical Conductivity, Redox Potential

Because *In situ* measurement device was not available at the field so soil samples were analysed in the laboratory. Before measurement, soil samples were air-dried and sieved through 2 mm mesh. Only soils <2 mm were used for these determinations. All laboratory devices were calibrated as instructed by the manufacturers. Electrical conductivity and pH were determined using by HACH portable multi meter. Built-in temperature sensor of the multimeter allowed to measure the temperature of the sample at the same time.

## **pH**

10 ml of each soil sample and 50 ml of potassium chloride were added in an Erlenmeyer flask and mixed in 2 hours. The suspension was then transferred to a beaker and mixed on a magnetic stirrer while the pH was measured.

## **Conductivity (EC)**

Before measuring soil samples, a blank sample of distilled water was measured. If the conductivity of the blank sample is over 1 mS/s, the ORP meter need to be recalibrated. 20g of each soil sample and 100 ml of distilled water were added to an Erlenmeyer flask and shook for 30 minutes to form water suspensions. The mixtures were allowed to stand for 30 minutes before filtered by filter paper. The conductivity determination was performed on filtered solution.

## **Redox Potential (ORP)**

Redox Potential was determined by inoLab pH Level 1. 25 ml of each soil sample and 50 mL distilled water were added in an Erlenmeyer flask and mixed in 30 minutes. The suspension was then transferred to a beaker and mixed on a magnetic stirrer while the redox potential was measured.

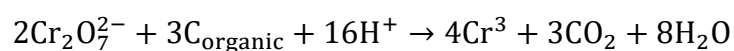




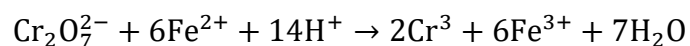
FIGURE 6. inoLab pH Level 1 and redox potential sensors

### 3.4.2 Total Organic Carbon (TOC)

Total Organic Carbon (TOC) was determined by titration. An amount of excessed potassium dichromate with acid sulfuric oxidized organic carbon to carbon dioxide.



The excessed  $\text{K}_2\text{Cr}_2\text{O}_7$  that remained unreacted was then determined by ferrous sulphate titration. (Radojevic & Bashkin, 2006, pp. 312–315).



The experiment procedure was performed on ten soil samples and a blank sample and their replicas as follows: First, 0,5g of prepared soil sample was added into an Erlenmeyer flask with exactly 5 ml  $\text{K}_2\text{Cr}_2\text{O}_7$  0,8125N and 20 ml of  $\text{H}_2\text{SO}_4$  and mixed together. The mixture was left stand for 30 minutes. Next, 100 ml distilled water and 10 ml  $\text{H}_3\text{PO}_4$  were added into the flask and cooled down to room

temperature. Three drops of n-phenylanthranilic acid 0,1% were added as indicator and the suspension was titrated with  $(\text{FeSO}_4 (\text{NH}_4)_2\text{SO}_4 \cdot 6\text{H}_2\text{O})$ .



FIGURE 7. Set up of TOC analysis

The TOC of the soil was calculated using the following formula:

$$TOC(\%) = \frac{(a - b) \times 0,4 \times c}{m} \quad (10)$$

In which:

a is volume of ferrous ammonium sulphate used in blank sample (ml)

b is volume of ferrous ammonium sulphate used in soil sample (ml)

m is weight of soil sample (g)

c is molar concentration of ferrous ammonium sulphate (mol/l)

The organic matter content in soil can be converted from the TOC by the following equation:

$$OM(\%) = TOC \times 1,724 \quad (11)$$

## 4 RESULTS AND DISCUSSION

### 4.1 Dioxins analysis

In this section, total concentrations of 17 PCDDs/PCDFs and 2,3,7,8-TCDD are presented. The mass concentration and TEQ of each chemical can be found in Appendix 1.

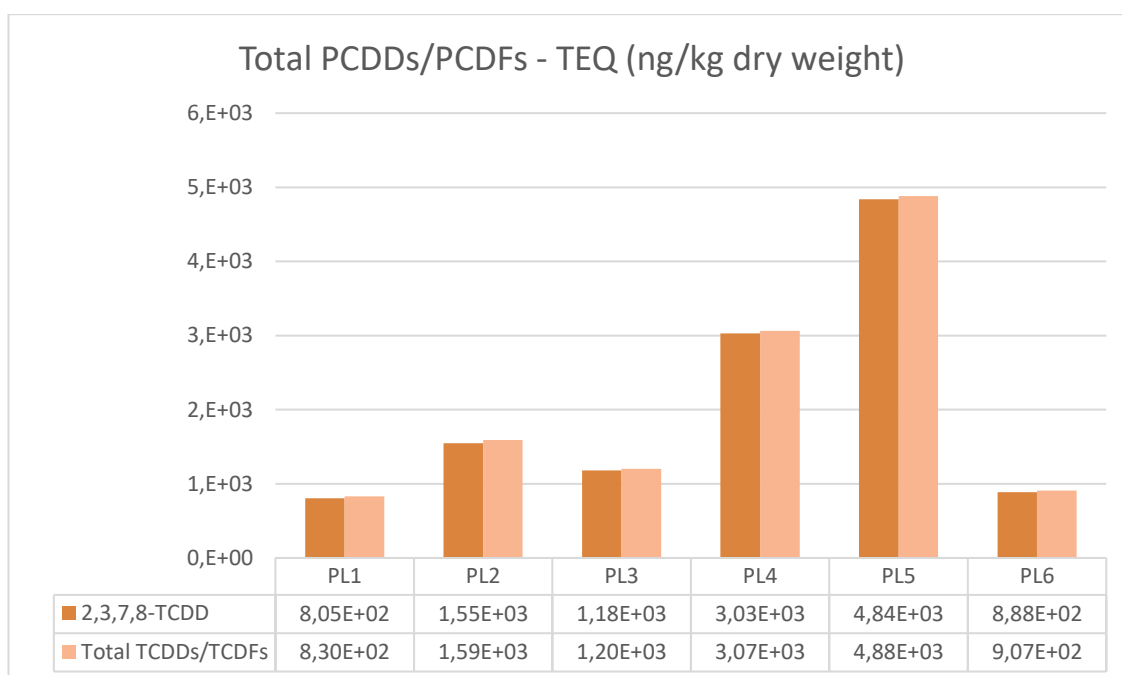


FIGURE 8. Total concentration PCDDs/PCDFs of dioxin contaminated soil

The total concentration of PCDDs/PCDFs ranged from  $8,30E+02$  ng/kg in PL1 to  $4,88E+03$  ng/kg in PL5. 2,3,7,8-TCDD, which was used as reference compound for TEF because of its highest toxicity, had TEF value of 1 so its TEQ and mass concentration were equal (Berg et al., 2006). Figure 8 shows that 2,3,7,8-TCDD was dominant in the toxic chemical group. However, when assessing the threshold of the toxins in soil, total TEQ of all PCDDs/PCDFs is considered.

Dioxin contaminated soil samples were taken from land that were categorized as land used for industrial purpose. According to QCVN 45:2012/BTNMT: National Technical Regulation on Allowed Limits of Dioxins in Soils, issued together with Circular No. 13/2012/TT-BTNMT, with effect from December 2012, all sample plots' total TEQs, except PL1 and PL6, exceeded the limit for industrial purpose

(1200 ng/kg TEQ subject to dry weight) (Ministry of Natural Resources and Environment, 2012). Comparing to the thresholds in regulations that some countries set on dioxins in soil, these samples' values were also well above them (Tu et al., 2014).

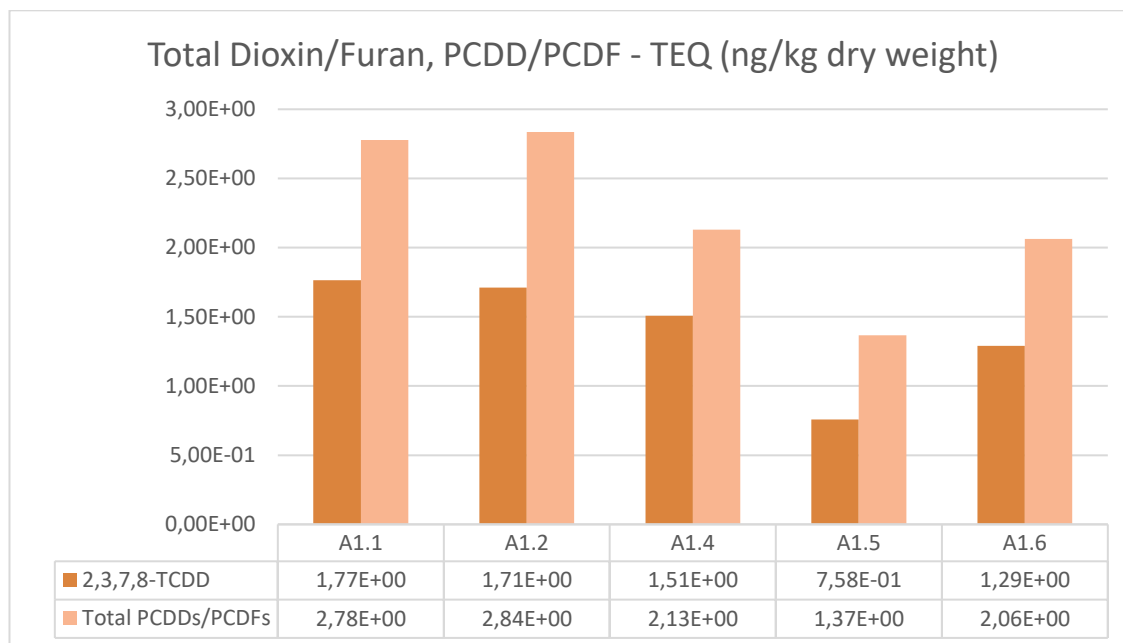


FIGURE 9. Total concentration PCDDs/PCDFs of normal soil

In normal sample group, 2,3,7,8-TCDD comprised over half of the TEQ. The TEQ of PCDDs/PCDFs in normal soil samples was unnoticeable comparing to that in contaminated soil samples. These values are also in permitted level for urban land (300 ng/kg TEQ subject to dry weight), which is the land type of these sample plots (Tu et al., 2014).

## 4.2 Physical properties

### 4.2.1 Soil density and particle-size distribution

Soil density test was carried out for calculation of the particle size distribution. The density of the soil is shown in Table 2.

TABLE 2. Soil density calculated for the samples

	Sample	Soil density (g/cm <sup>3</sup> )
Normal soil	A1.1	2,68
	A1.2	2,68
	A1.4	2,68
	A1.5	2,67
	A1.6	2,67
Dioxin contaminated soil	PL1	2,70
	PL2	2,72
	PL3	2,69
	PL4	2,70
	PL5	2,71
	PL6	2,71

The composition of the soil by four grain types: gravel, sand, silt and clay is illustrated in the graph below. The distribution by particle diameter can be found in Appendix 2 and 3.

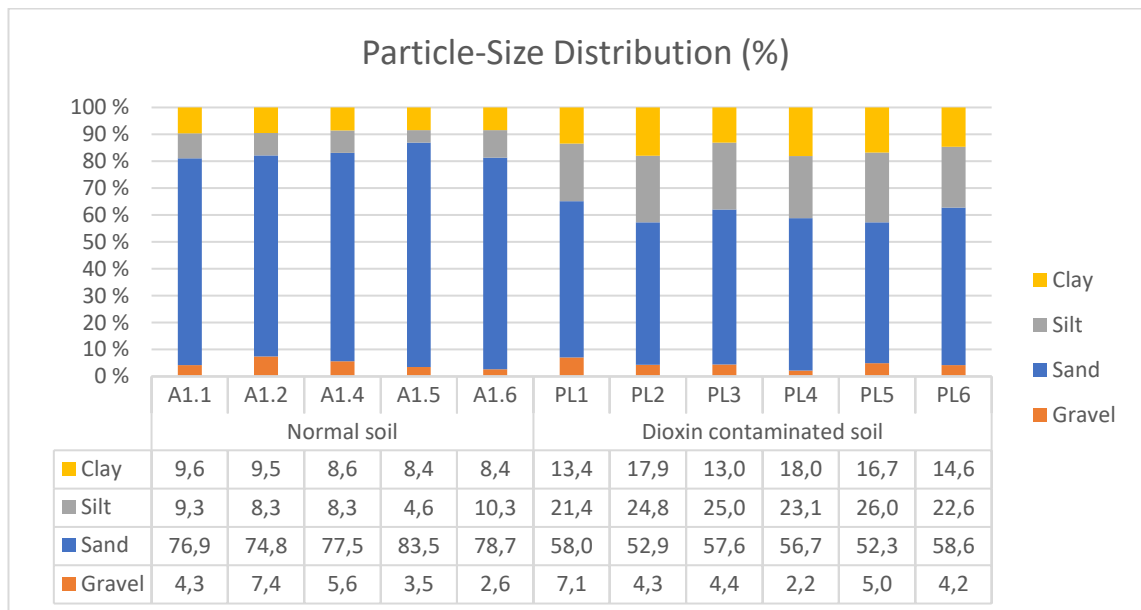


FIGURE 10. Particle-Size distribution of normal soil and dioxin contaminated soil

Because there were no additional analysis such as liquid limit and plasticity index conducted, the soil samples could not be classified into soil groups. However, soil texture classes can be identified based on sand, silt and clay proportion. According to USDA soil triangle, all normal soil samples were loamy sand and all dioxin contaminated soil samples were sandy loam. Sand was the major type of grain in all samples. (USDA NRCS, n.d.). Non-contaminated soil samples had

significant sand content, over 74%. The sand proportion in contaminated soil samples were lower, as their silt and clay content took over one-third of the share. No noticeable difference in the gravel percentage between normal and dioxin contaminated soil was observed.

Early findings said that the grading of soil is a major factor controlling soil properties (Carter & Bentley, 2016, pp. 35–36). It was expected if two sample types shared similar grain size composition, it would be more favorable for the study of dioxin impact on soil properties. However, the high percentage of silt and clay in dioxin contaminated soil may pose as an explanation on the persistence of dioxin in these soil samples. A previously study by Stranberg explained that fine soil has lower permeability and higher capability in establishing bonds with dioxin thanks to its higher surface-area-to-volume ratio than coarse soil (Strandberg et al., 2011). Hence, when combine these factors with the insolubility in water and high adsorption to soil organic carbon of dioxin, it can be understood that dioxin resisted against water-related force such as rain, extending its half life longer than normal and still remain in this soil at high concentration.

On the contrary, the soil in which dioxin concentration was very low was coarser. It is worth mentioning that this sample area was also suspected as a storage area for herbicide during Pacer Ivy mission and some studies in the past has reported contamination of dioxin in this area (USAID, 2016). Therefore, particle-size distribution influences permeability and influences the retention of dioxin in soil. Furthermore, a dioxin contamination physical treatment technique which uses water-based solvent called soil washing was report as not effective on soils with high clay, silt and organic matter content due to similar reasons (Strandberg et al., 2011).

#### **4.2.2 Wet Aggregate Stability**

Wet aggregate stability (WAS) is one of important factors indicating the soil quality (Petruzzelli et al., 2016, pp. 83–84). As one of the thesis's target was to support the main project which concerns the use of vetiver grass as a remediation

for dioxin contamination in soil and discuss the future perspective of dioxin remediation, it is important to study the stability of the soil structure. The wet aggregate stability of dioxin contaminated soil analysed in this thesis can be a useful reference for comparison of the soil quality before and after dioxin treatment in future studies.

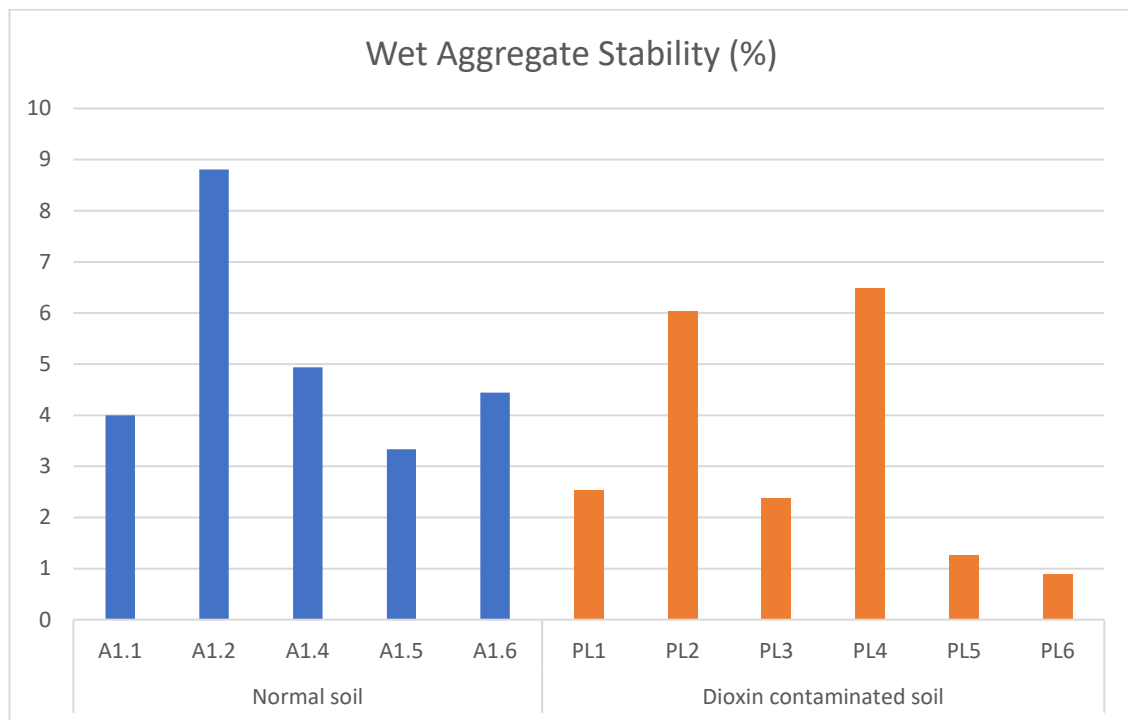


FIGURE 11. Wet Aggregate Stability of normal and dioxin contaminated soil

The figure above depicts the wet aggregate stability of both sample groups. No sample had 1-2 mm aggregates rate higher than 10%, hence, these soils had very low stability against impact by water (Hazelton & Murphy, 2016, p. 27). Although the aggregate stability values in each group relatively varied from each other, which dioxin contaminated samples had lower soil aggregation in general. It is noticeable that A1.2, PL2 and PL4 had exceptionally higher WAS than others in their groups. Wet aggregate stability is associated with other soil properties such as soil structure, extractable cations, organic matter and microorganism activity in soil (USDA NRCS, 2008). It is said that clay and organic matter act as binding agents in soil, hence enhance the potential of aggregation (Ding & Zhang, 2016). Total organic carbon (TOC) of these samples, which is proportional to organic matter content, were also higher than others' (see Figure 15). On the contrary, the relationship between sand fraction and aggregate by wet sieving was reversed, the higher the amount of aggregates, the lower the coarse fraction.

Study on soil aggregate stability carried out by Ding and Zhang drew the same conclusions (Ding & Zhang, 2016).

Another factor can be taken into consideration is the effect of plant growth in improving the soil quality. Research by Petruzzelli suggested that vetiver grass was grown in sample plot PL2 for 4 years, contributed to the increase in the organic matter and the stability of the soil structure. (Petruzzelli et al., 2016).

### **4.3 Chemical properties**

#### **4.3.1 pH. Electrical Conductivity. Redox Potential**

In this section, electrochemical measurements will be discussed. As mentioned above, samples were air-dried, sieved and analysed in the laboratory instead of field measurement. Although this laboratory method produced results less representative of the field condition than using fresh samples, it was acceptable since all soils measured in the same way were comparable (Radojevic & Bashkin, 2006).

#### **pH**

pH is one of the most common parameters measured when it comes to soil properties. The acidity and alkalinity of soil, which are indicated by pH, provide valuable information on soil characterization such as chemical processes and nutrient availability in soil (Radojevic & Bashkin, 2006). While dioxin contaminated soil samples were mildly alkaline to moderately acid (pH from 5.95 to 7.78), normal soil samples were strongly acid (pH from 4.35 to 5.57) (see Figure 12) (Hazelton & Murphy, 2016, p. 60).

The pH range of dioxin contaminated soil is optimal for the growth of many plants. On the other hand, low pH values in non-contaminated soil mean nutrient deficiencies and possible aluminium toxicity (Hazelton & Murphy, 2016).



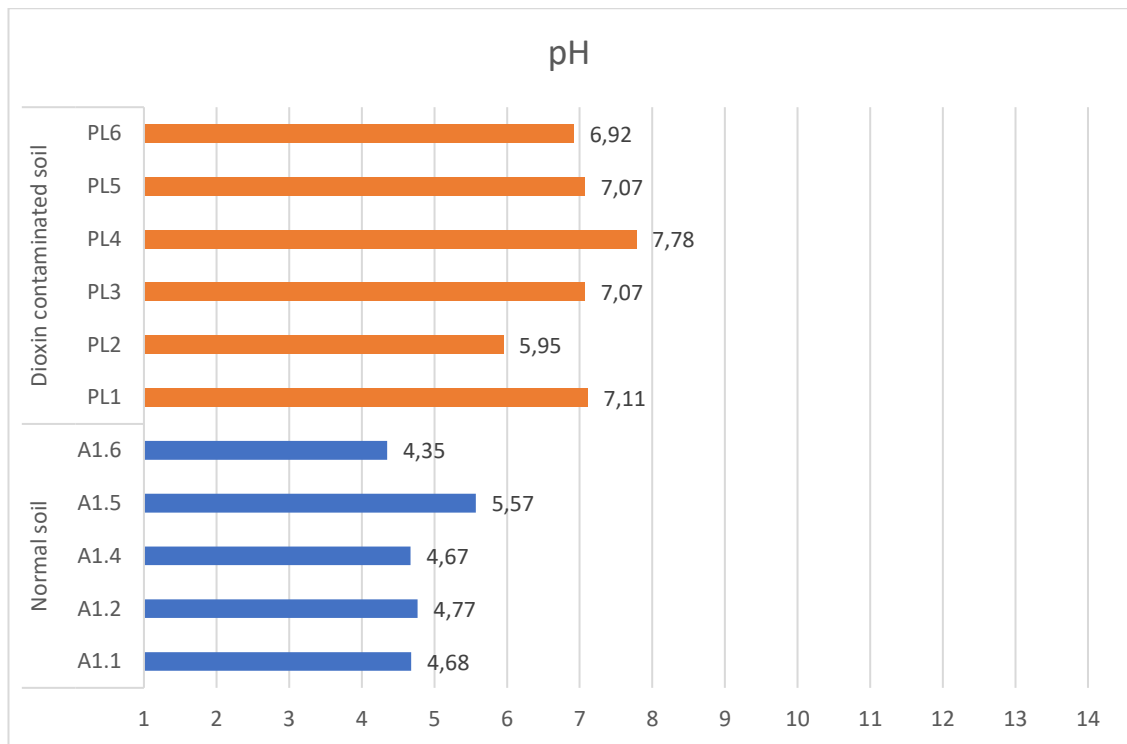


FIGURE 12. pH values measured for normal and dioxin contaminated soil

### Redox potential

The measurement of redox potential in soil is simple, but it can be very difficult to apply the results in a general context and compare them with other literature because redox potential highly varies in different conditions and it is less studied in soil science, especially when compared to pH. Nevertheless, it cannot be denied that ORP plays an important role in monitoring the fate of pollutants and nutrients in soils, thus, it is a key soil quality indicator (Husson, 2013).

The ORP value of all samples were very low (see Figure 13), indicating that the soils were in reducing condition to highly reducing condition and thus, not ideal for cultivation (Husson, 2013). On the other hand, highly reduced soils might be favourable for the development of some bacteria, especially anaerobic bacteria. Interestingly, dioxin contaminated soil samples, which were collected at deeper layer than normal soil samples, had higher Eh while some studies mentioned that soils at deeper subsurface may had lower Eh (Husson, 2013; Radojevic & Bashkin, 2006).

As stated in Methods section, the ORP results obtained in the laboratory was only practical for comparison between the soils and could not reflect the redox potential in the field condition because redox potential differs substantially in soils at field, fresh soils brought to laboratory and dried soils (Radojevic & Bashkin, 2006). There was, however, lack of information on the correlation of ORP in different soil conditions, so it is inadequate to conclude about the biological and biogeochemical processes in the soils.

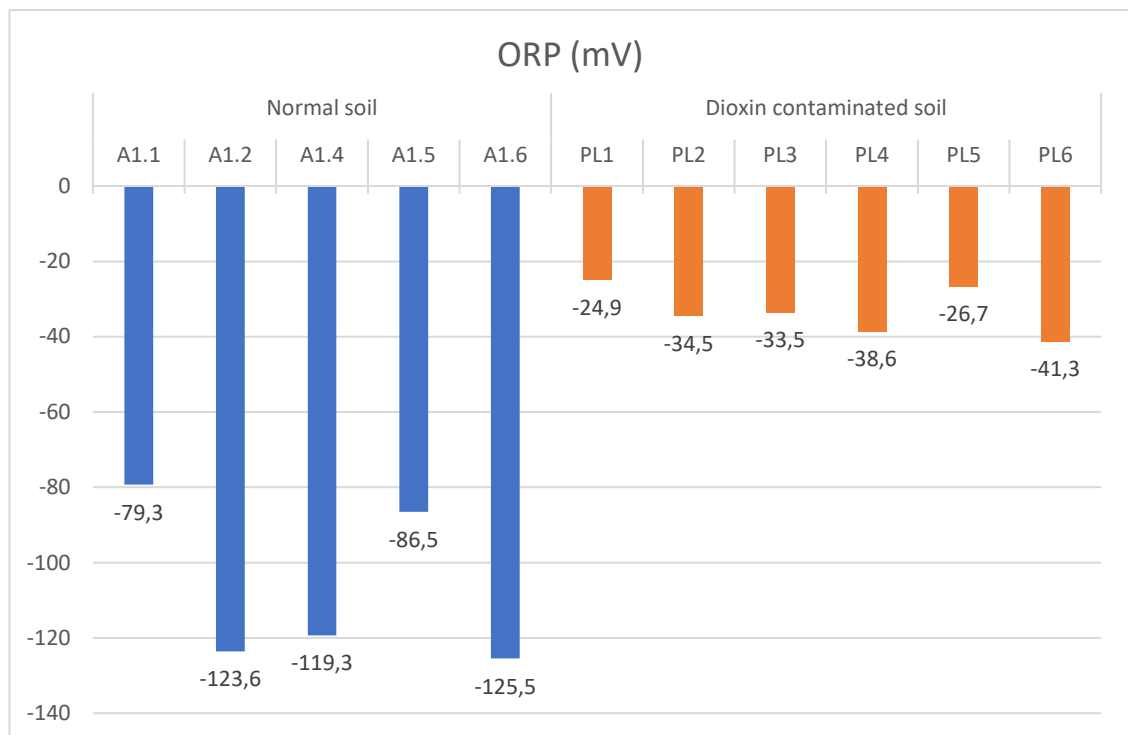


FIGURE 13. Redox Potential of normal and dioxin contaminated soil

### Electrical Conductivity

Another important parameter of soil quality is soil electrical conductivity, which interprets soil salinity and soil capacity to store nutrient. While very high soil conductivity (over 16 ECe dS/m) reveals that soil is extremely saline and affect most crops, in non-saline soil, which ECe is lower than 2 dS/m, the higher the EC value, the better the nutrient availability. (Hazelton & Murphy, 2016, p. 82; USDA NRCS, 2014).

In this case study, all soil samples have very low to low soil salinity rating (see Figure 14) (Hazelton & Murphy, 2016). Dioxin contaminated soil had higher EC

than normal soil as a result of higher clay content. In addition, the time that the samples were taken could possibly contribute to higher EC values. PL-soil samples were taken in October, the end of raining season, so rainwater carrying soluble salts penetrated into deeper soil layer. (USDA NRCS, 2014).

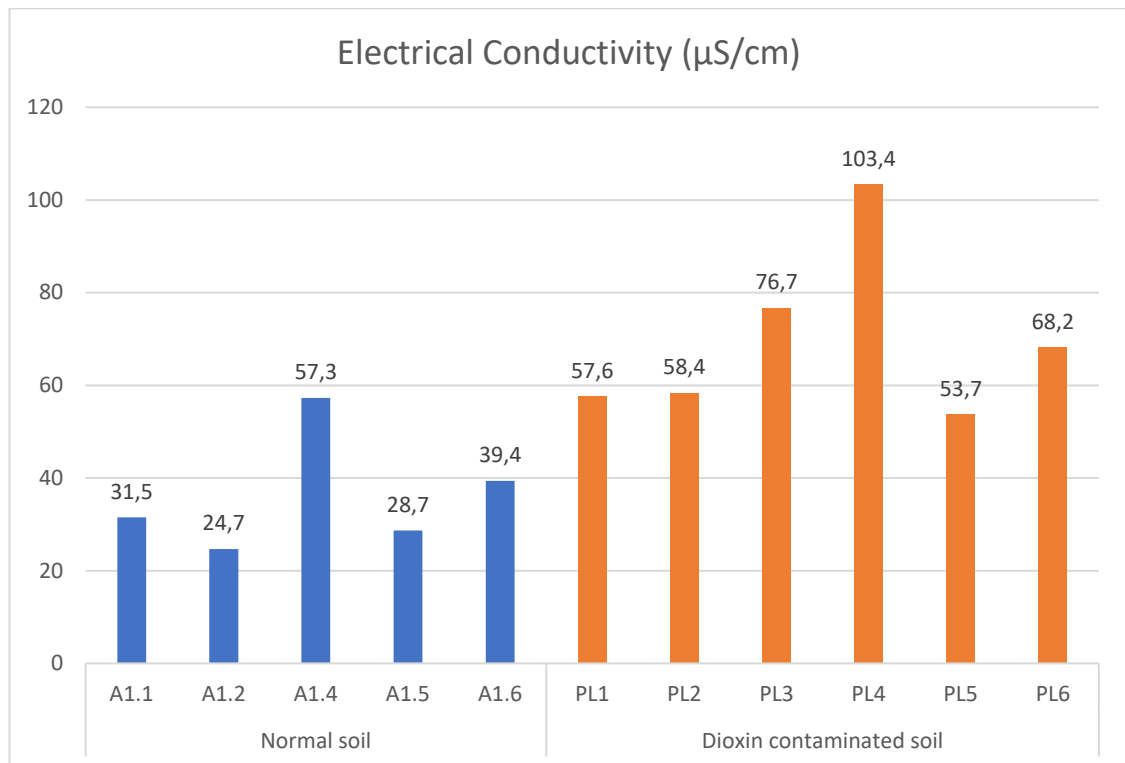


FIGURE 14. Electrical Conductivity values for normal and dioxin contaminated soil

#### 4.3.2 Total Organic Carbon

Total organic carbon is an expression for organic matter. Normally, organic matter is calculated by multiplying organic carbon level with 1,72 (Hazeltan & Murphy, 2016). However, this conversion factor is only relative and varied so here only organic carbon value is presented (see Figure 15).

The highest organic carbon content was found in A1.4 - normal soil sample, at 0,89%. Normal soils had higher TOC values than dioxin soil, which were between 0,47-0,89%, while that of dioxin contaminated soils were between 0,27-0,57%. According to soil organic matter rating by Hazeltan & Murphy, most samples had very low to low organic matter level, except PL1, 5 and 6, which TOC level were

considered extremely low. These values reflect the poverty of soil structural condition and stability, which correspond with wet aggregate stability results (see Figure 11). Research in the past suggested that there be serious erosion and degradation observed in PL1, 5 and 6. (Hazelton & Murphy, 2016).

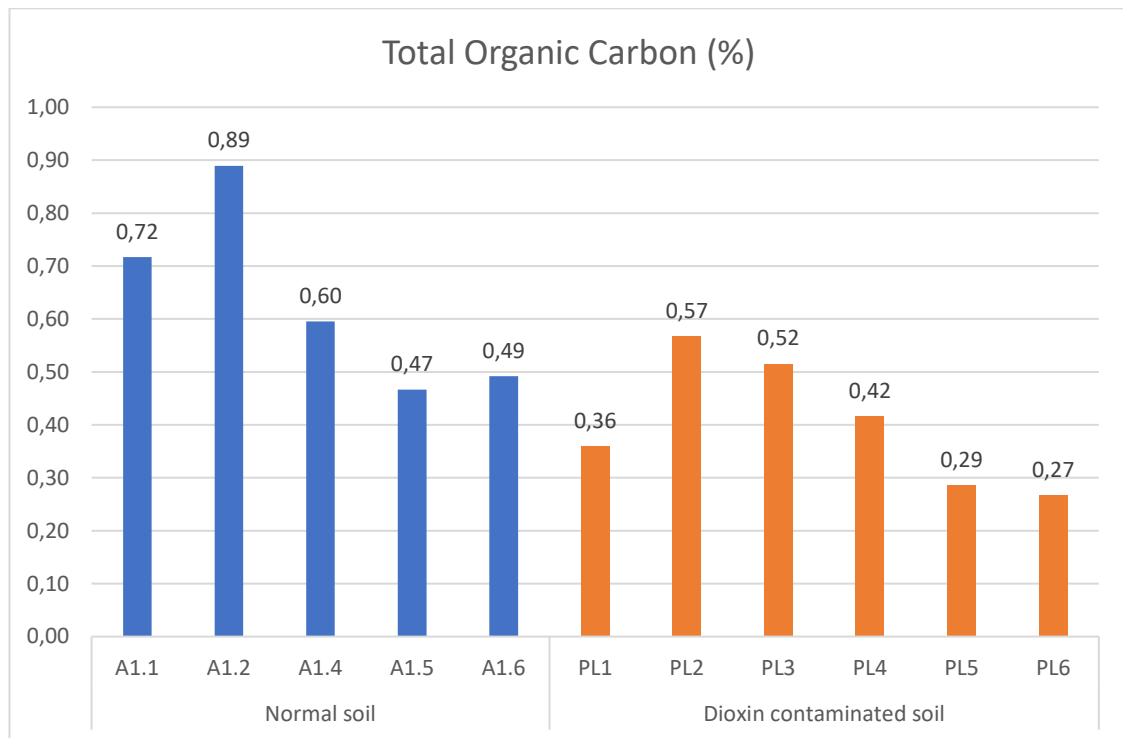


FIGURE 15. Total Organic Carbon of normal and dioxin contaminated soil

A number of natural factors impact on organic matter content, pH, soil texture and vegetation, for instance, were noticeable in this case. The normal soil sampling area was overgrown with weeds. The amount of organic matter accumulated thanks to the decomposition of grass leaves and roots, which contained high lignin content. In dioxin contaminated soil, PL2 and PL4 had higher TOC as a result of higher clay content comparing to the rest of the group. Soils with higher clay content increase two processes, one is the bonding of organic matter with the surface of clay particles and the other is the formation of aggregate. Finally, as all soil samples' pH were generally acidic and their structure were extremely poor, limiting biomass production, thus the rate of organic matter was very limited. (Bot & Benites, 2005, pp. 11–13).

## **4.4 Future perspectives**

In this section, limitations of this thesis will be reviewed for improvement and a different approach to the experiment results, which will open a discussion for dioxin contaminated soil treatment methods, will be presented.

### **4.4.1 Limitations and suggestions for future research**

First, the results expose a few constraints in the sampling methods. The two sample groups were collected in different seasons, so the changes of weather and field conditions were accountable for the insufficient comparability of the electrical conductivity. The way the samples were processed may cause problems in redox potential readings. It was proved that redox potential was the most problematic parameter which could be affected by several outside factors.

Although the total organic carbon determination was acceptable for addressing the differences between the two soils, titration experiment performed in this study had certain limitations that could affect the use of the results as a reference for future research. Organic carbon determined by dichromate back-titration is possibly interfered by inorganic carbon and human errors. The combustion method, which is performed by automatic analyser, is more reliable and accurate. The TOC analyser was planned to be used for double-checking of the TOC results by titration, but unfortunately the available instrument was not adequately equipped for dioxin contaminated soil analysis.

Second, the shortage of research on the behaviour of dioxin in soil and the characteristic of dioxin contaminated soil posed as the biggest obstacle in linking the dioxin with the soil quality. There was no previous study provided relevant information on the soil properties of other dioxin contaminated sites for referencing and comparison. In addition, the variety of samples used for this study was not sufficient to clearly illustrate possible relationship between dioxin contamination and soil property.

Based on discussed limitations, the following measures could be applied in future research. Sampling should be carried out in the same period for all samples, weather conditions must be noted and discussed if they are attributable to the anomaly of the results. The sample groups can be more diversified, especially when referencing materials are limited. Some of the laboratory analysis cannot replace field measurements. Therefore, it is advisable to conduct measurements both at the field and in the laboratory to ensure meaningful results.

#### **4.4.2 An environmentally sustainable approach for dioxin remediation**

A complete recommendation for dioxin treatment technologies must be based on various criteria and requires intensive effort as well as advanced knowledge. Remediation method recommendation for dioxin contaminated soil at Bien Hoa Air-base is only a subobjective of the thesis, thus it is limited in the scope of this thesis, that suggestions are approached from environmental aspect of remediation process, incorporated with the findings of soil quality indicators discussed above.

Incineration, despite of being the most efficient technology, will have significant effects on the environment if not closely monitored and well planned with mitigation measures. This technology will require extensive energy for the incineration process, thus produce substantial amount of GHGs. Moreover, the ash that is produced from the incineration process will require a landfill, which may be an environmental risk in the long run. It should be noticed that incineration pose a public concern on incineration off-gassing. Meanwhile, ISTD/IPTD or *ex situ* TCH, which was identified as environmentally preferred technology for dioxin remediation, still possibly has potential or significant environmental consequences, remarkably substantial GHG emissions and carbon footprint. (USAID, 2016, pp. 291–292).

On top of that, all thermal treatment technologies while eliminate dioxins all so destruct organic matters, microbial communities in the soil leading to damage in other soil properties, such as aggregate stability. Aggregate stability is a key soil

property affecting fertility rate. Changes in soil fertility may interfere the restoration of the vegetation on treated soil. Organic matter is also a crucial quality parameter for agricultural soil. The loss of organic carbon may result in poor soil structure. These impacts lead to limitation in possibilities for land use after remediation. They were not considered in the EAs of either Bien Hoa Airbase or Danang Airport. Considering the decomposition of soil elements caused by thermal treatment can bring adverse effects on soil quality, minimum effective treatment temperature should be used to avoid unnecessary soil decomposition and understand the thermal properties of soil constituents. This will not only benefit the ecosystem recovery after treatment but also reduce carbon footprint and costs. (Vidonish et al., 2016).

The rate of degradation is influenced by multiple factors, comprising the characteristics of the contaminants, environmental conditions, availability of the microorganisms. For instance, the effectiveness of microbiological treatment is highly dependent on environmental conditions, such as carbon content, availability of electron donors and acceptor and other physical-chemical parameters such as pH and temperature. (Urbaniak, 2013, pp. 77–79). Therefore, understanding the current status of soil quality will help determine appropriate environmental biodegradation method for dioxin.

Phytoremediation is probably the most environmentally friendly alternative amongst the treatment technologies reviewed in remediation technologies overview section, but its efficiency is not high in term of required implementation time. The active landfill is undoubtedly not a recommendable method in environmental perspective yet bioremediation using microorganisms without landfill is not. A previously study suggested that a combination of phytoremediation and biological remediation and the utilization of interaction in the rhizosphere between plant system, microorganisms and soils can boost the effectiveness of the treatment process and improve the soil quality. This symbiosis profits the biodegradation of dioxin in soil in multiple ways. On the one hand, the plant rhizosphere houses precious sources of carbon such as carbohydrate and amino acids, as well as other photosynthesis products for microorganisms. Substances released by plants enhance microbial activity and other biochemical processes in the soil

around the plant and in the root system. On the other hand, actively microorganism protect plants from stressing factors and promote plant nutrient uptake and contaminant destruction. The microorganisms and plants chosen for the remediation process must be well adapted to the soil conditions and the contamination level so as to maximize the effectiveness of biodegradation. (Urbaniak, 2013, pp. 83–84).

In Bien Hoa Airbase case, the soil quality assessed in this thesis was very poor (acidic, very low organic carbon content and aggregate stability and so on) thus the airbase's soil is not an ideal environment for the growth of many plants. Vetiver grass (*Chrysopogon zizanioides* L.) has been known for its high tolerance against contaminants such as herbicides and pesticides and extreme environment conditions such as highly acidic soil, drought, and lack of organic matter thanks to its special morphological and physiological characteristics. Vetiver grass has a deep and massive root system, allowing the root to penetrate into the soil and create a big rhizosphere, benefiting microorganism activities and contaminants treatment activities. (Truong, 2000). These advantages make vetiver grass a potent candidate for rhizoremediation of dioxin contaminated soil at Bien Hoa Airbase. This combined method cannot succeed without the addition of microorganism. The negative soil redox potential showed the aerobic condition of the soil. As mentioned in previous sections, anaerobic bacteria develop in highly reduced soil condition and could dechlorinate more chlorinated dioxins better than aerobic microorganisms. A study by Mäntynen denoted chlorination rates were better when temperature range were above 20-27°C (Mäntynen, 2018). The annual average temperature in Bien Hoa is over 20°C, so the temperature is sufficient for an efficient treatment. However, available research on the bioremediation of dioxin did not elaborate on specific condition requirement for the growth of different anaerobic microorganism species so there should be more case studies at Bien Hoa Airbase on the use of anaerobic microorganisms in dioxin remediation to confirm the hypothesis.



## 5 CONCLUSIONS

The study has found significantly high concentration of PCDDs/PCDFs in soil samples from Pacer Ivy area ( $8,30E+02$  ng/kg in PL1 to  $4,88E+03$  ng/kg dry weight), 4 over 6 samples exceed the GVN limits. 2,3,7,8-TCDD occupied over 90% of the weight. In samples collected from Southwest area, PCDDs/PCDFs concentration was insignificant and well above the GVN limit for urban area.

The fate of dioxin in soil, including degradation, is affected by its physical-chemical characteristics and a number of environment factors including clay content, pH, moisture and organic matter. High clay content found in dioxin contaminated soil might be a factor contributing to the high residual dioxin concentration in the samples as dioxins persist in soil by binding to clay particle and organic carbon. Another interesting finding was the quality of the dioxin contaminated soil was not necessarily worse than non-contaminated soil. This was illustrated by more optimal pH value and better EC value. Both soil groups had very poor structure and low organic carbon content although these figures of normal soil were slightly better. Normal soils were also more reduced than contaminated soils, but all samples had negative redox potential.

Although these parameters when standing alone will not have much meaning, but they will serve as useful references when considering remediation alternatives and assessing the impact of remediation technology on soil quality. High temperature in thermal treatment such as incineration and *ex situ* TCH can cause decomposition of organic matter, which may alter soil fertility, limiting the vegetation recovery of the treated area and soil reuse purposes. With regard to more sustainable remediation alternatives, remediation combining phytoremediation and bioremediation is highly potential. Dioxin degradation is improved through interactions between plants, plant rhizospheres, soil and microorganisms. However, it is important to select type of plant and microorganism that can adapt to the environment and the dioxin input.

Based on the soil characteristic of the study area, vetiver grass and anaerobic microorganisms are excellent candidate for the combined environmental

remediation of the dioxin contamination in soil at Bien Hoa Airbase. Vetiver grass show superiority over other plants thanks to its high environmental tolerance and its massive root systems which promotes microorganism activities and thus promote dioxin remediation process. There is no specific recommendation for anaerobic bacteria species because of the lack of information on detailed living conditions for different microorganisms so more case studies at Bien Hoa Airbase should be conducted.

In general, the thesis has adequately assess the soil quality at Bien Hoa Airbase and give recommendation on environmental benign remediation for dioxin contaminated soil. However, the study has showed some limitations in the choice of methods and implementation. The lessons for future research include examining more diverse samples, avoiding the interference of environment factors by conducting measurements in the same period, the same manner and with both field equipment and laboratory equipment.

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## APPENDICES

Appendix 1. PCDDs/PCDFs concentration in soil samples (ng/kg dry weight)

1 (4)

Name		A1.1	A1.2	A1.4	A1.5	A1.6
2378-TCDD		1,712	1,712	1,507	0,758	1,290
12378-PeCDD		0,413	0,413	0,201	0,177	0,282
123478-HxCDD		0,260	0,260	0,149	0,155	0,203
123678-HxCDD		1,156	1,156	0,714	0,706	0,732
123789-HxCDD		1,399	1,399	1,139	0,906	1,096
1234678-HpCDD		16,990	16,990	5,132	6,118	8,336
OCDD		225,920	225,920	81,359	116,520	142,590
2378-TCDF		0,238	0,238	0,162	0,174	0,214
12378-PeCDF		0,178	0,178	0,169	0,112	0,229
23478-PeCDF		0,219	0,219	0,146	0,175	0,152
123478-HxCDF		0,375	0,375	0,186	0,216	0,187
123678-HxCDF		0,217	0,217	0,147	0,189	0,164
234678-HxCDF		0,257	0,257	0,192	0,184	0,207
123789-HxCDF		0,188	0,188	0,156	0,116	0,162
1234678-HpCDF		2,419	2,419	1,174	1,244	1,433
1234789-HpCDF		0,187	0,187	0,075	0,125	0,116
OCDF		5,484	5,484	2,111	2,636	3,039
<b>Toxic Equivalent TEQ</b>	<b>WHO 2005 TEF</b>					
2378-TCDD	1,00E+00	1,77E+00	1,71E+00	1,51E+00	7,58E-01	1,29E+00
12378-PeCDD	1,00E+00	3,36E-01	4,13E-01	2,01E-01	1,77E-01	2,82E-01
123478-HxCDD	1,00E-01	2,30E-02	2,60E-02	1,50E-02	1,60E-02	2,00E-02

123678-HxCDD	1,00E-01	1,01E-01	1,16E-01	7,10E-02	7,10E-02	7,30E-02
123789-HxCDD	1,00E-01	1,59E-01	1,40E-01	1,14E-01	9,10E-02	1,10E-01
1234678-HpCDD	1,00E-02	1,30E-01	1,70E-01	5,10E-02	6,10E-02	8,30E-02
OCDD	3,00E-04	4,80E-02	6,80E-02	2,40E-02	3,50E-02	4,30E-02
2378-TCDF	1,00E-01	1,50E-02	2,40E-02	1,60E-02	1,70E-02	2,10E-02
12378-PeCDF	3,00E-02	8,00E-03	5,00E-03	5,00E-03	3,00E-03	7,00E-03
23478-PeCDF	3,00E-01	5,90E-02	6,60E-02	4,40E-02	5,30E-02	4,60E-02
123478-HxCDF	1,00E-01	2,70E-02	0,00E+00	1,90E-02	2,20E-02	1,90E-02
123678-HxCDF	1,00E-01	2,20E-02	2,20E-02	1,50E-02	1,90E-02	1,60E-02
234678-HxCDF	1,00E-01	2,60E-02	2,60E-02	1,90E-02	1,80E-02	2,10E-02
123789-HxCDF	1,00E-01	2,80E-02	1,90E-02	1,60E-02	1,20E-02	1,60E-02
1234678-HpCDF	1,00E-02	2,80E-02	2,40E-02	1,20E-02	1,20E-02	1,40E-02
1234789-HpCDF	1,00E-02	1,00E-03	2,00E-03	1,00E-03	1,00E-03	1,00E-03
OCDF	3,00E-04	1,00E-03	2,00E-03	1,00E-03	1,00E-03	1,00E-03
<b>Total PCDDs/PCDFs – TEQ</b>		<b>2,78E+00</b>	<b>2,84E+00</b>	<b>2,13E+00</b>	<b>1,37E+00</b>	<b>2,06E+00</b>

Name		PL1	PL2	PL3	PL4	PL5	PL6
2378-TCDD		805,000	1547,000	1184,000	3027,000	4837,000	888,000
12378-PeCDD		10,900	23,200	10,800	22,800	27,500	9,330
123478-HxCDD		3,450	9,530	3,300	4,720	31,100	3,370
123678-HxCDD		20,400	34,900	16,500	30,800	27,500	13,300
123789-HxCDD		14,700	25,000	10,000	19,400	14,900	11,400
1234678-HpCDD		330,000	276,000	150,000	196,000	165,000	200,000
OCDD		2346,000	1044,000	1051,000	1216,000	1029,000	1466,000
2378-TCDF		24,500	27,500	30,900	54,700	45,800	30,300
12378-PeCDF		3,150	5,160	1,850	2,750	1,650	1,890
23478-PeCDF		4,920	11,500	2,920	5,610	4,080	2,780
123478-HxCDF		7,380	13,900	2,920	3,930	4,460	2,680
123678-HxCDF		3,450	12,500	1,750	1,970	1,750	2,280
234678-HxCDF		6,500	16,500	1,650	1,670	1,070	2,680
123789-HxCDF		0,591	3,770	<0,500	<0,500	<0,500	<0,500
1234678-HpCDF		41,500	54,400	19,100	18,000	22,400	21,600
1234789-HpCDF		1,180	5,860	0,875	<0,500	<0,500	0,893
OCDF		46,100	35,600	25,300	19,300	26,700	33,600
<b>Toxic Equivalent TEQ</b>	<b>WHO 2005 TEF</b>						
2378-TCDD	1,00E+00	8,05E+02	1,55E+03	1,18E+03	3,03E+03	4,84E+03	8,88E+02
12378-PeCDD	1,00E+00	1,09E+01	2,32E+01	1,08E+01	2,28E+01	2,75E+01	9,33E+00
123478-HxCDD	1,00E-01	3,45E-01	9,53E-01	3,30E-01	4,72E-01	3,11E+00	3,37E-01
123678-HxCDD	1,00E-01	2,04E+00	3,49E+00	1,65E+00	3,08E+00	2,75E+00	1,33E+00
123789-HxCDD	1,00E-01	1,47E+00	2,50E+00	1,00E+00	1,94E+00	1,49E+00	1,14E+00
1234678-HpCDD	1,00E-02	3,30E+00	2,76E+00	1,50E+00	1,96E+00	1,65E+00	2,00E+00
OCDD	3,00E-04	7,04E-01	3,13E-01	3,15E-01	3,65E-01	3,09E-01	4,40E-01
2378-TCDF	1,00E-01	2,45E+00	2,75E+00	3,09E+00	5,47E+00	4,58E+00	3,03E+00



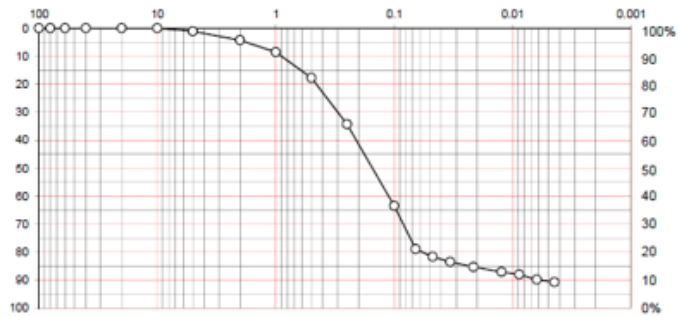
12378-PeCDF	3,00E-02	9,45E-02	1,55E-01	5,54E-02	8,26E-02	4,95E-02	5,66E-02
23478-PeCDF	3,00E-01	1,48E+00	3,46E+00	8,75E-01	1,68E+00	1,22E+00	8,34E-01
123478-HxCDF	1,00E-01	7,38E-01	1,39E+00	2,92E-01	3,93E-01	4,46E-01	2,68E-01
123678-HxCDF	1,00E-01	3,45E-01	1,25E+00	1,75E-01	1,97E-01	1,75E-01	2,28E-01
234678-HxCDF	1,00E-01	6,50E-01	1,65E+00	1,65E-01	1,67E-01	1,07E-01	2,68E-01
123789-HxCDF	1,00E-01	5,91E-02	3,77E-01	0,00E+00	0,00E+00	0,00E+00	0,00E+00
1234678-HpCDF	1,00E-02	4,15E-01	5,44E-01	1,91E-01	1,80E-01	2,24E-01	2,16E-01
1234789-HpCDF	1,00E-02	1,18E-02	5,86E-02	8,75E-03	0,00E+00	0,00E+00	8,93E-03
OCDF	3,00E-04	1,38E-02	1,07E-02	7,58E-03	5,78E-03	8,01E-03	1,01E-02
<b>Total PCDDs/PCDFs – TEQ</b>		<b>8,30E+02</b>	<b>1,59E+03</b>	<b>1,20E+03</b>	<b>3,07E+03</b>	<b>4,88E+03</b>	<b>9,07E+02</b>

Appendix 2. Particle-Size Distribution

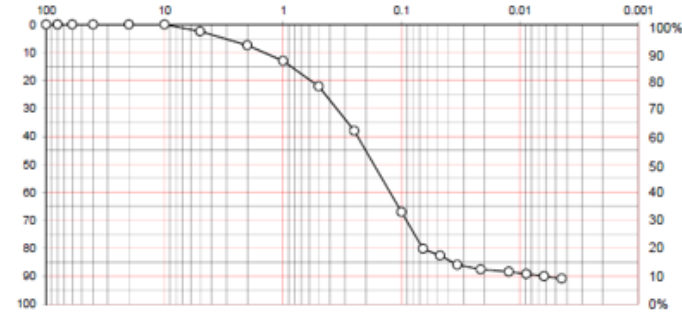
		PARTICLE-SIZE DISTRIBUTION (%) BY PARTICLE DIAMETER (mm)												
		Gravel			Sand						Silt			Clay
		5-10	2-5	Total	1-2	0,5-1	0,25-0,5	0,1-0,25	0,05-0,1	Total	0,01-0,05	0,005 - 0,01	Total	<0,05
		%	%	%	%	%	%	%	%	%	%	%	%	%
Normal soil	A1.1	1,1	3,2	4,3	4,3	9,2	16,6	29,2	17,7	76,9	6,5	2,7	9,3	9,6
	A1.2	2,4	5,0	7,4	5,6	9,1	15,9	29,1	15,2	74,8	6,7	1,6	8,3	9,5
	A1.4	1,5	4,1	5,6	3,0	8,6	16,4	30,0	19,4	77,5	6,2	2,1	8,3	8,6
	A1.5	0,2	3,3	3,5	3,3	7,6	22,9	31,8	17,9	83,5	2,1	2,5	4,6	8,4
	A1.6	0,3	2,3	2,6	3,0	7,9	16,8	31,4	19,6	78,7	7,4	2,9	10,3	8,4
Dioxin contaminated soil	PL1	2,2	4,9	7,1	6,3	15,7	13,4	13,2	9,5	58,0	11,6	9,9	21,4	13,4
	PL2	1,5	2,8	4,3	5,5	12,8	11,4	13,9	9,4	52,9	14,5	10,3	24,8	17,9
	PL3	1,7	2,7	4,4	4,3	12,0	13,8	16,0	11,5	57,6	13,5	11,5	25,0	13,0
	PL4	0,2	2,0	2,2	4,9	12,4	14,0	14,8	10,5	56,7	13,1	10,0	23,1	18,0
	PL5	1,3	3,7	5,0	6,2	14,0	11,6	12,9	7,6	52,3	14,3	11,7	26,0	16,7
	PL6	0,5	3,7	4,2	5,4	14,5	13,6	14,0	11,1	58,6	13,3	9,3	22,6	14,6

### Appendix 3. Particle-Size Distribution Curve

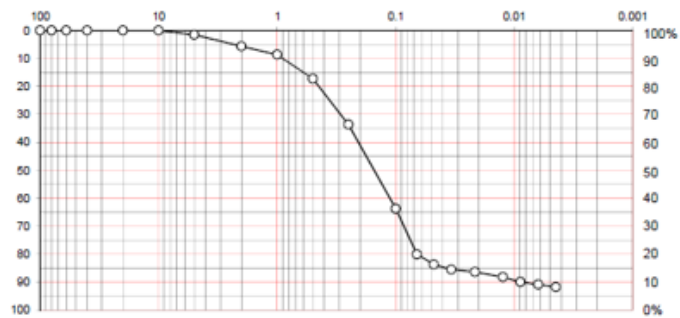
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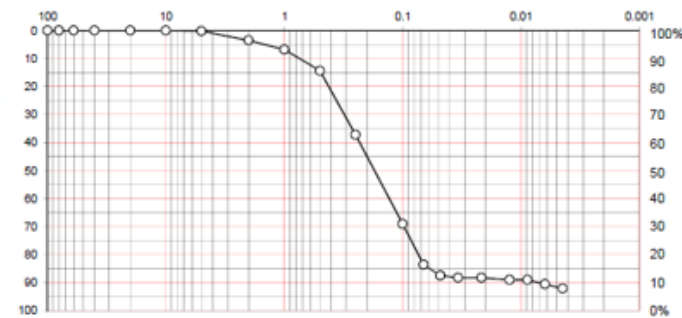
A1.1



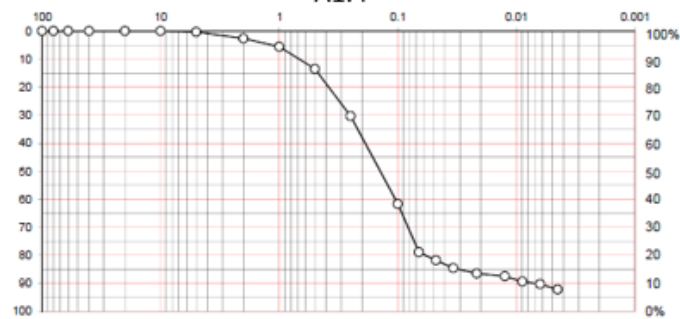
A1.2



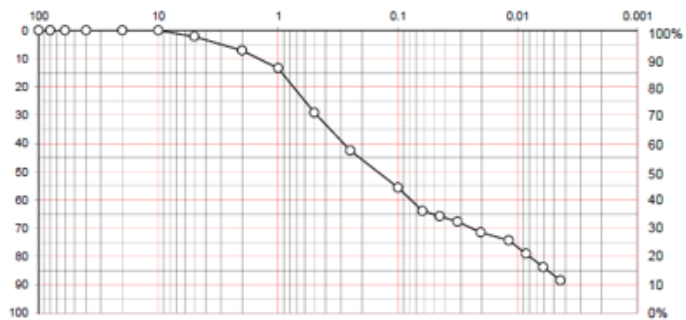
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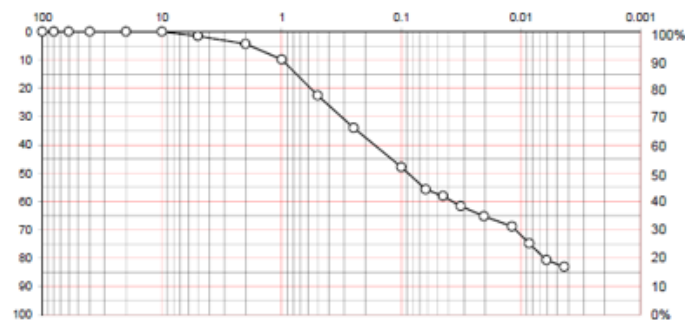
A1.5



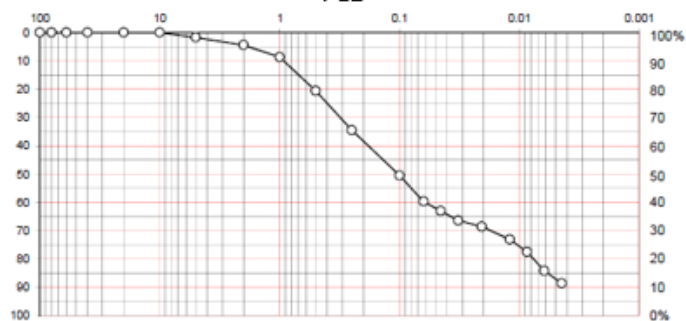
A1.6



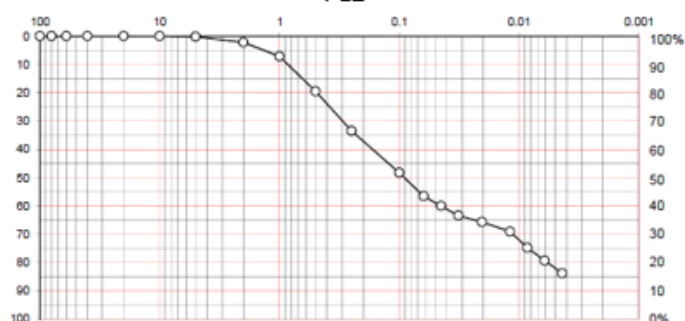
PL1



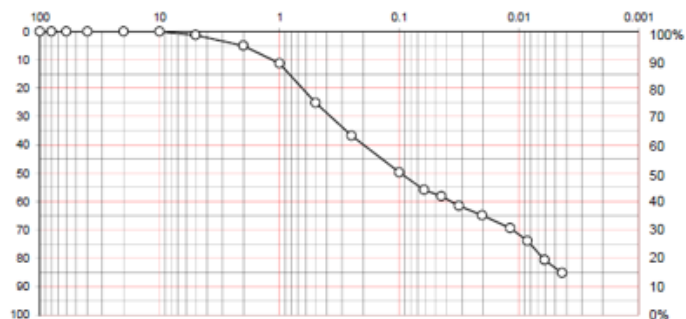
PL2



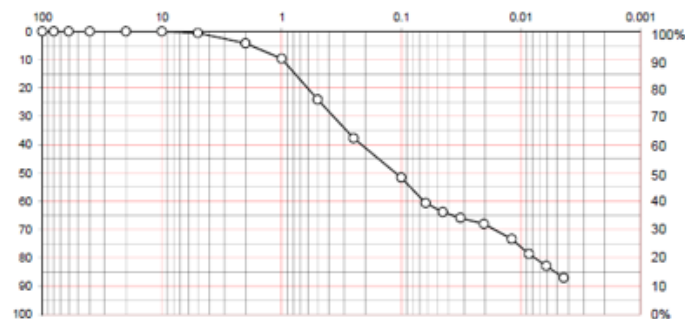
PL3



PL4



PL5



PL6