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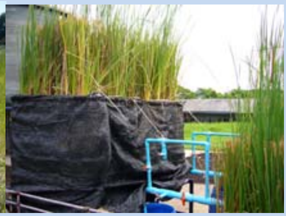
72

Nathasith Chiarawatchai

Implementation of earthworm-assisted constructed wetlands to treat wastewater and possibility of using alternative plants in constructed wetlands



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Technische Universität Hamburg-Harburg

aww
Institut für Abwasserwirtschaft und Gewässerschutz

Implementation of earthworm-assisted constructed wetlands to treat wastewater and possibility of using alternative plants in constructed wetlands

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Abstract

The aim of this research was to investigate the potential of integrating earthworms into the constructed wetlands in order to realize whether they could mitigate clogging problems as well as to improve the treatment performances. The experiment was conducted in Germany and the implementation was also undertaken in Thailand, in which the raw domestic wastewater was used in Germany and swine wastewater was used in Thailand. Apart from these issues, there was also a matter concerning resource efficiency of the wetlands, especially with respect to plants. Utilization options of plants were explored and alternative plants with high resource recovery potential were proposed.

As there was no prior research with respect to this issue, the study firstly investigated the presence of earthworms within a constructed wetland in Germany. Its objective was to explore whether earthworms were already a part of the biocommunities within the system. The results from different seasons revealed the existence of earthworms within the wetland's substrate. This suggested that it could provide a suitable habitat for them and they could thrive within the constructed wetlands.

The results from the lab-scale studies in both countries revealed that earthworms could help alleviating the problem of clogging, especially with respect to swine wastewater treatment. Also, earthworms were proved to thrive within the wetland body. For the pilot-scale study in Germany, the results showed that the vertical-flow constructed wetlands with earthworms performed in most case superior to the one without earthworms. The unplanted unit with earthworms was also assembled for comparison purpose and its treatment performance was the worst. Hence, it could be stated that earthworms should be integrated into the constructed wetlands rather than the unplanted constructed wetlands.

Another lab-scale study in Thailand demonstrated that the vertical subsurface-flow constructed wetlands with earthworms followed by horizontal ones had generally the best treatment performance. Scale-up of the experiment was designed based on this configuration. There was a minor difference in terms of the removal efficiency while comparing the units with earthworms to the ones without in the pilot-scale study. The removal efficiency in most parameters was higher than 90%. The production of sludge on the surface was reduced by 40% with earthworms. This indicated the benefit of integrating earthworms into the constructed wetlands. Further research could be undertaken in order to find the optimal condition to apply the earthworms inside the wetlands effectively.

For the proposal of alternative plants, several criteria were investigated. In most cases the nutrient uptakes were relatively minor. No significant differences in terms of treatment efficiency could be found. The cost differences of plant propagules between each species are marginal. Based on an investigation of 44 species worldwide, the recommendation table was developed with 13 suitable species that fitted all the criteria. It revealed that there are more than one "most appropriate plant species" in each climatic region. To perform the selection, the operators should weigh their preferences on the criteria according to their priority and the availability of plants in the area.

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1 Introduction

1.1 Background

Constructed wetlands are considered as one of the natural systems being applied to treat wastewater. Compared to mechanical treatment concepts (e.g. activated sludge, tricking filter, etc.), natural treatment system in most cases results in a system that costs less to build and to operate, and requires significantly less energy (Reed et al. 1995). The trade-off between these advantages lies in the dimensions of space and time, in which natural treatment requires both aspects more to provide efficient level of treatment. The system particularly suits developing countries as well as any rural or low density area in the world. In such cases, the conventional systems that may be appropriate in industrialized regions and densely populated areas with guaranteed power supplies, easily replaceable parts, and a skilled labor force to ensure operation and maintenance requirement might not be suitable for those regions with limited resources (Denny 1997).

Among the types of constructed wetlands, there has been a rapid application of subsurface-flow constructed wetlands (SFCWs) to treat wastewater. In the UK, there are approximately 1000 units in operation (Cooper 2007). They can be classified according to the feed pattern as horizontal subsurface-flow constructed wetlands (HSFCWs) and vertical subsurface-flow constructed wetlands (VSFCWs). Wastewater flowing to SFCWs normally requires some form of preliminary treatment, usually a septic tank, in order to reduce its strength and potential of clogging inside the system (Reed et. al. 1995). With respect to its operation, one major disadvantage which has been pointed out by several works, especially for the VSFCWs, is the potential for clogging (Blazejewski and Murat-Blazejewska 1997, Crites and Tchobanoglous 1998).

Clogging of wetland media reduces their void spaces, causing the decrease of hydraulic conductivity. Usually this situation occurs due to solid accumulation at the surface or at the change between the substrate gradients for VSFCWs. For HSFCWs, it occurs at the substrates located around the inlet structure, which can result in surface flow of wastewater. This can negatively affect the overall treatment performance as well as its operational lifetime. The susceptibility of this problem particularly rises in accordance with the strength of wastewater. Generally, the problem can be dealt with by increasing the rest periods between each feeding cycle in VSFCWs (Breen 1997) and/or by lowering the hydraulic loading rate (HLR) as well as organic loading rate. However, the design loading rate of wastewater into the wetland body will be affected. This could be an economically limiting factor in terms of land requirement as lowering the loading rate while keeping the wastewater quantity constant implies that a larger surface area is needed.

One study in Australia reported the presence of earthworms at the inlet of several non-clogged HSFCWs treating grey water, and the lab-scale experiment reported that earthworms could move the sludge within the saturated substrates to the surface (Davison et al. 2005). Hence, earthworms might be a promising solution to deal with clogging, as they by nature can ingest the organic matter and will then deposit their casts on or near to the surface. Although it seems possible theoretically, in order to respond to the argument whether it would be scientifically and technically sound to introduce earthworms into the SFCWs, one could also look further into the substrates within the constructed wetlands whether earthworms do actually reside there. Although such investigation was conducted at the HSFCWs, no similar study was conducted on the VSFCWs. Hence, one aim of this research is to investigate the presence of earthworms within the VSFCWs.

Basically, the treatment system using earthworms has been widely applied to treat the solid and animal wastes (Edwards 2004), as well as sewage sludge (Khwairakpam and Bhargava 2009, Prince et al. 1981, Vigueros and Camperos 2002), and human faeces (Shalabi 2006). This process is called vermicomposting, where earthworms fragment the waste substrates as well as enhance microbial activity and the rates of decomposition of the material. This leads to composting or humification effect, in which the unstable organic matter is oxidized and stabilized.

Still, both VSFCWs and the application of earthworms have never been combined together into a single treatment unit apart from being used separately. Therefore, another aim of this research is to implement this concept by introducing earthworms into the surface of SFCWs and to investigate their potentials to reduce clogging and/or improve the treatment efficiency. Because of the potentials of earthworms in terms of clogging reduction, the earthworm-assisted SFCWs could be able to cope with a raw domestic wastewater, i.e. the wastewater that does not enter septic tank. Therefore, this application can be implemented to treat such high-strength wastewater, such as animal wastewater.

Focusing on Thailand, swine farming has undergone a rapid growth in order to feed the fast-increasing population and to serve the new culture of meat consumption. This has raised significant concern over the problem regarding swine wastewater in the country (TDA 1997). Both VSFCWs and HSFCWs could be applied to treat such wastewater in Thailand. They are among the treatment technologies applied to treat such wastewater (Lee et al. 2004, Kantawanichkul et al. 2003, Prantner et al. 2001).

Nevertheless, as swine wastewater possesses exceptionally high strength, the potential of clogging due to extremely high solid contents in the swine wastewater is inevitably stronger than those of domestic wastewater. Even the SFCWs pre-treated by anaerobic digesters also have experienced this problem (Alvarez et al. 2008). As the application of using earthworms to treat swine manure is widespread (Edwards 2004, Gunadi and Edwards 2003), they could also be possibly integrated into the SFCWs in order to tackle this problem and combine both solid and wastewater treatment process into a single treatment system. Therefore, the aim of this research part in Thailand is to investigate the potential of applying earthworms into constructed wetlands receiving swine wastewater in Thailand. In this case, an issue with respect to the transfer of this technology from the temperate climate of Germany, where the first part of this research was conducted to the tropical climate of Thailand, as well as the corresponding design of the system such as the choice of plants and the characteristic of wastewater, are also taken into consideration.

Apart from the issue of applying earthworms into the SFCWs as well as transferring the technology to Thailand for treating swine wastewater, there is also a matter concerning resource efficiency, especially with respect to plants. Generally, common reed (*Phragmites australis*) is among the most popular plants used in constructed wetlands because of high tolerance and abundance in several areas of the world (Kadlec and Knight 1996). Nevertheless, the harvest of reed, which is generally conducted at the end of the growing season, has been less focused. Open burning of plants after the harvest is a common practice at several SFCWs. In terms of nutrient recovery, this method represents a waste of resource. Moreover, there is no harvest at all in several cases, such as the constructed wetlands in the Czech Republic (Vymazal 1996).

Under such circumstances, a major part of the nutrient that is accumulated by plants might be recycled to the water (or soil) again (Kadlec et al. 2000). Hence, it might be more economical and ecological-sound if plants that possess more utilization options are used rather than the conventional ones so that the stakeholders can plan their use after harvest effectively. This can guarantee that the resources will not be wasted, and instead will be appropriately used. This potential, if appropriately managed, could to some extent return the costs of the overall treatment system (Wissing and Hoffmann 2002). Furthermore, it could expand the possibilities to use other alternative plants in the area where no common wetland plant is available. Hence, another aim of this study is to analyze the plants that have been applied into the constructed wetlands and to propose the suitable alternative macrophytes that possess high resource recovery efficiency in SFCWs without any negative effects to the treatment performance.

1.2 Objectives

The main objectives of this thesis were divided into 4 parts, in which three of them were undertaken in Germany and the last one was conducted in Thailand.

1. Investigating the potentials of utilizing alternative plants which possess more utilization options based on each climatic region
2. Investigating the probability of finding earthworms that might be resided as part of the biocommunity within the VSFCWs
3. Investigating the potential of using earthworms in the lab- and pilot-scale constructed wetlands to treat raw domestic wastewater in Germany
4. Investigating the potential of applying this concept in the lab- and pilot-scale constructed wetlands to treat swine wastewater in Thailand

1.3 Structure of the dissertation

The first chapter, **chapter 1**, provides the background and problem statement, as well as the objectives of this study. The following chapters are outlined as follows:

Chapter 2 discusses the overview of constructed wetlands technology, including the processes and associated problems, whereas **chapter 3** presents the overview of vermicomposting process. Its role and application concerning domestic wastewater and swine wastewater are reviewed here. Both chapters represent detailed theoretical investigation and the current state of knowledge with respect to each technology. The applications of both technologies in Thailand are also included. Moreover, an elaboration of why implementing this system should be theoretically feasible is discussed.

The following chapter, **chapter 4**, outlines the methodologies used in this study. In **chapter 5**, the results are presented and discussed. Each section within both chapters are outlined according to each respective objective; the determination of alternative plants to be used in constructed wetlands, the presences of earthworms within VSFCWs, the experiments in Germany, and finally the experiments in Thailand. The conclusions of this study are presented in **chapter 6**, which also discusses the recommendations for further research.

2 Overview of the constructed wetlands technology

2.1 Background of constructed wetlands

In principle, a nature-based wastewater treatment technology aims to utilize the processes that primarily depend on natural components to achieve any intended purposes. It can be classified into three major categories, which comprise aquatic, terrestrial, and wetland concepts (Reed et. al. 1995). Aquatic systems include the use of ponds or lagoons on the one hand, and aquaculture, which also utilize the higher plants and animals on the other hand. For terrestrial treatment systems, they consist of slow-rate, rapid-infiltration, and overland-flow system. Historically, the land application was the first emerged natural technology around the nineteenth century and constructed wetlands were the newer development concept occurring during the 1970s.

Constructed wetlands are defined as those wetlands which are specifically constructed for treating wastewater and are effective in the removal of BOD, TSS, and nitrogen (Brix 1994). Their origins were based on the initial works of Dr. Seidel in 1966 who investigated the role of common bulrush *(Scirpus lacustris)* in wastewater treatment. Since then, numerous concepts and systems have been derived from her studies. Therefore, the term "constructed wetlands" could be historically ascribed to Seidel. The beneficial uses of these systems for wastewater treatment are well established, and the technology continues to develop rapidly (Price and Probert 1997).

Typically there are three types of constructed wetlands (Crites et al. 2000). The first is called free-water surface wetlands (FWS), in which the water surface is exposed to the atmosphere. There is similarity to the natural wetlands because this system can be described as a pond containing aquatic plants that are rooted in the soil layer at the bottom. The wastewater flows through the leaves and stems of the plants. Their design and operation are very close to pond systems. The second and the third can be grouped into the subsurface-flow types (SFCWs), in which the difference lies mainly on the feeding pattern, either vertically- (VSFCWs) or horizontally-fed (HSFCWs). For the HSFCWs, water level is maintained below the top of the porous media which is usually gravel (Reed et al. 1995). VSFCWs are characterized by an intermittent (discontinuous) feeding where wastewater vertically percolates through a substrate layer that mainly consists of sand, gravel or a mix of these.

As the main focus and the content of this research are based on the SFCWs type, the corresponding overview concerning FWS was omitted and further mention of the term “wetlands” or “constructed wetlands” is referred to those of subsurface types. The diagram of each type is illustrated in figure 2.1.

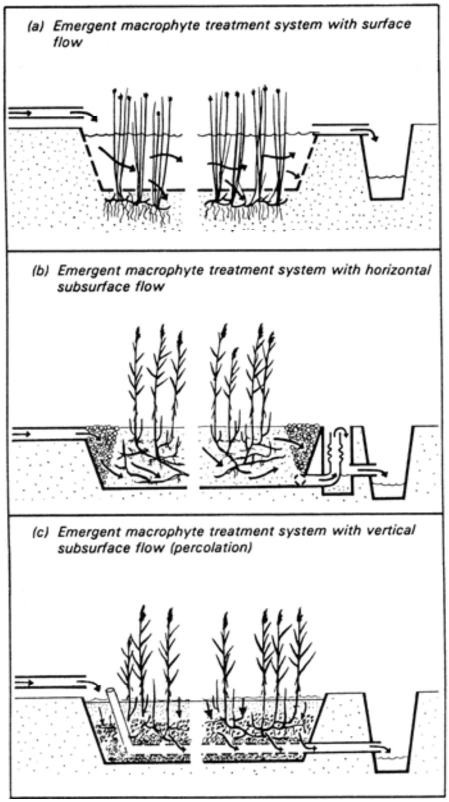

Figure 2.1: Schematic presenting each type of constructed wetlands, in which a: FWS, b: HSFCWs, and c: VSFCWs (Brix 1993)

However, the spread of the use of constructed wetlands to developing countries has been depressingly slow, particularly due to the problem associated with technology transfer. In Thailand, there were few researches concerning SFCWs undertaken, particularly one in Chiang Mai comprising a uniquely-designed VSFCWs over a HSFCWs in one unit (Kantawanichkul et al. 2003), and one utilizing the VSFCWs planted with narrow-leaf cattails at the Asian Institute of Technology (AIT), Pathumthani (Koottatep et al. 2005). Apart from those being built for research purposes, after the Tsunami in 2004, the constructed wetlands were constructed to practically treat wastewater in several southern regions, namely the 3-stages HSFCWs at Baan Pru Teau, the VSFCWs followed by HSFCWs, FWS, and polishing pond respectively at Koh Phi Phi Don island, and the HSFCWs treating river water at Patong, Phuket (Brix et al. 2007). Therefore, this technology has already been established to some extent in Thailand.

2.2 Processes within the SFCWs

Treatment processes in constructed wetlands incorporate several physical, chemical, and biological processes. The major physical process is the settling of suspended particulate matter which is a major cause of BOD reduction. The chemical processes involve adsorption, chelation, and precipitation, which are responsible for the major removal of phosphorus and heavy metals. In terms of biological processes, the treatment is achieved by microorganisms (Gopal 1999). Due to fixed film or free bacterial development, biological processes allow the degradation of organic matter, nitrification in aerobic zones and denitrification in anaerobic zones. The principal removal mechanisms in SFCWs for some constituents in wastewater are summarized in table 2.1;

Table 2.1: Principal removal and transformation mechanisms in SFCWs for the concerned constituents in wastewater (modified after Crites and Tchobanoglous 1998)

Constituent	Mechanisms
Biodegradable organics	Bioconversion by facultative and anaerobic bacteria on plant and debris surfaces
Suspended solids	Filtration, sedimentation
Nitrogen	Nitrification/denitrification, plant uptake, volatilization
Phosphorus	Filtration, sedimentation, plant uptake
Heavy metals	Adsorption of plant roots and debris surfaces, sedimentation
Trace organics	Adsorption, biodegradation
Pathogens	Natural decay, physical entrapment, filtration, predation, sedimentation, excretion of antibiotics from roots of plants

With regards to the role of plants in constructed wetlands, they mainly contribute to the nutrient transformation process. Although the direct uptake of nutrient is considered minor, the buried parts in SFCWs serve as a large surface area for dense and diversified populations of attached microorganisms such as bacteria, protozoa as well as certain algae species to enhance microbial activities. Litter, fallen plant materials and detritus also provide additional surface areas and attachment sites for microbial growth (Tanner 2001). Such buried plant tissues provide a habitat for a vast diversity of microbial communities due to diversified and complex conditions that include anaerobic, aerobic and anoxic microsites, oxygen releases, and root exudates (Wissing and Hoffmann 2002). Moreover, they offer mechanical resistance to flow, increase the retention time, facilitate settling of suspended particulates, and improve conductance of water through the media as the roots grow. Furthermore, they transport oxygen to the deeper layer of the media and hence assist in oxidation and precipitation of heavy metals on the root surfaces (Gopal 1999).

In order to maximize the benefit in SFCWs, it is important to encourage root penetration to the full depth of the media so that potential contact points could be available throughout the profile (Reed et al. 1995). The most frequently used plants species are *Scirpus* sp. (bulrush), *Typha* sp. (cattail), and *Pragmites* sp. (reeds). Their typical characteristics are described below in table 2.2.

Table 2.2: Typical characteristics of plant species used in constructed wetlands (modified after Crites and Tchobanoglous 1998, Reed et al. 1995)

Characteristic	Bulrush	Cattail	Reeds
Distribution	Worldwide	Worldwide	Worldwide
Preferred temperature (°C)	16-27	10-30	12-23
Preferred pH range	4-9	4-10	2-8
Salinity tolerance (ppt*)	20	30	45
Root penetration (m)	≈ 0.6	≈ 0.3	≈ 0.4
Drought resistant	moderate	Possible	high
Growth	Moderate to rapid	Rapid	Very rapid

*ppt: parts per thousand

As stated previously, there are two types of SFCWs to be discussed. Both possess different characteristics. The key advantage of VSFCWs is an improved oxygen transfer into the soil layer. Beside oxygen input by the plants and diffusion processes that also occur in HSFCWs, there is more significant oxygen into the substrates through convection caused by the intermittent feeding in the case of VSFCWs (Platzer 1998). This additional aeration of the soil by convective processes allows higher nitrification as well as removal of organic matter. However, denitrification that requires anoxic conditions is usually lower (Bahlo and Ebeling 2007), as well as the removal of SS in comparison to the HSFCWs (Vymazal 2001). This is due to the flow pattern of HSFCWs, which is naturally continuous. Table 2.3 compares the effectiveness among each type of technology according to each environmental parameter.

Table 2.3: The effectiveness of each technology based on each parameter (European Commission 2001)

Type	Organic matter	TKN	Total N	Total P
HSFCWs	Yes	Poor nitrification	Good denitrification	No
VSFCWs	Yes	Good nitrification	Poor denitrification	No

In terms of the phosphorus removal, its main mechanism within the SFCWs is the adsorption of phosphorus to the substrates (e.g. gravel or sand) (IWA 2000). Nevertheless, the conventional substrates applied in SFCWs could not efficiently remove phosphorus. In order to improve the P-retention of constructed wetlands, substrates possessing higher phosphorus adsorption capacities, higher Ca, Fe, and Al contents, as well as larger particle surface areas and hydraulic conductivity are alternatively needed (Vymazal et al. 1998). Several studies have investigated the use of industrial by-products such as lightweight aggregates (LWA), in which one example of this product is called light expanded clay aggregate (LECA). Waste materials from industries as well as natural materials with higher adsorption capacities were also studied with respect to the capabilities to replace gravel or sand within the SFCWs designed for enhanced phosphorus removal (Johansson 1996, Brooks et al. 2000).

Normally, some forms of pre-treatment is required to preliminarily treat wastewater flowing to constructed wetlands, usually by applying a septic tank in order to reduce its strength and potential of clogging inside the system (Reed et al. 1995). In Europe, most of the development of SFCWs aims to replace both primary and secondary treatment to remove BOD and SS as well as inorganic nutrients (Mitsch and Jorgensen 2003). Apart from those parameters, several studies also reveal that SFCWs have been proved to be efficient in the removal of pathogens (Gerba et al. 1999, Green et al. 1997, Reed et al. 1995).

2.3 Problems with SFCWs

Based on the development of this technology, several obstacles have been presented such as the internal problem concerning clogging, or the external problem associated with related treatment components such as septic tank. Apart from the problem, one should also aim to make uses of SFCWs in a more sustainable way, such as increasing their biodiversity, or implementing the resource recovery measures. The resources from the latter term can be either plants or treated wastewater itself. This can guarantee that they would not be wasted, but appropriately used. Such practices could positively contribute to both ecological and economical aspects. The discussion is based on two aspects, on the problems as stated previously, and on further enhancement to efficiently recover the resources.

One major disadvantage of SFCWs is the potential for clogging as stated in the previous chapter, which has been pointed out by several works (Blazejewski and Murat-Blazejewska 1997, Crites and Tchobanoglous 1998). Clogging of wetland media reduces its void spaces and consequently hydraulic conductivity will be decreased. As a result, surface flow of wastewater can occur which will negatively affect the overall treatment performance.

In order to alleviate this problem, the presence of earthworms within the bed might offer a promising solution. Earthworms by nature can clean the substrate and will then deposit their casts on or near to the surface. The nutrient and carbon content in wastewater, in which some of them result in clogging matter, can be a food source for them. With this method as an enhancement of the system, there would be no need of septic tank system as the solid content initiating clogging within wetlands could be lowered by earthworms. Further discussion with respect to this principle is described in chapter 3 after a detailed overview of vermicomposting process is explained.

Apart from the clogging issue, one of the components in wastewater treatment system that poses several problems is the septic tank. In several cases, the accumulated sludge over the surface of the constructed wetlands is not disposed of in a proper measure, or there are leakages of the tank leading to groundwater contamination. In France, a particular VSFCWs design is developed by a company named SINT (La Société d'Ingénierie Nature et Techniques) with the back-up provided by CEMAGREF (Institut de recherche pour l'ingénierie de l'agriculture et de l'environnement), which aims to directly treat the raw wastewater so that the installation of the septic tank can be avoided (Boutin et al. 1997). The idea behind this system is that sludge management can be simpler by managing within the constructed wetlands in comparison with the conventional imhoff or digesting tank. Recently, there are more than 500 plants in France (Molle et al. 2005).

The design of this system can be categorized as two-stages VSFCWs, in which the 1^{st} stage consists of three alternately-fed beds and the 2^{nd} stage consists of two alternately-fed beds. The feeding phase generally lasts for 3 to 4 days. After that, the receiving bed is rested for twice this time in order to maintain an unsaturated condition within the wetland bodies as well as to mineralize the organic accumulated due to SS. The feed is in most cases regulated by siphons and the flows depend on the wastewater production. The system uses the special-designed siphon to maintain the hydraulic condition without an external energy source, provided that topography is appropriated (Molle et al. 2005). Schematic of the first-stage VSFCWs is shown in figure 2.2.

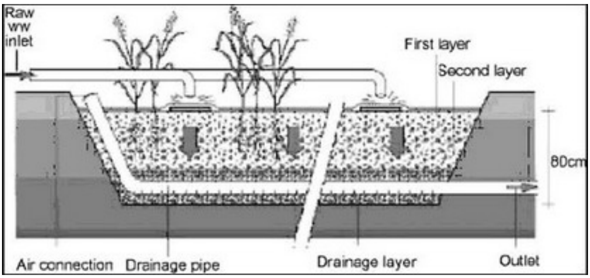

Figure 2.2: Schematic of the first stage French system (Molle et al. 2005)

Concerning the area requirement, in total 2 m^2/personal equivalent (PE) is required, in which 1.2 m^2/PE is attributed to the 1^{st} stage, and 0.8 m^2/PE is attributed to the 2^{nd} stage. Gravel is used as the main layer for the 1^{st} stage, whereas sand is used for the 2^{nd} stage. Both stages are also layered with the transition and drainage bed. The substrate configuration of each stage is depicted below.

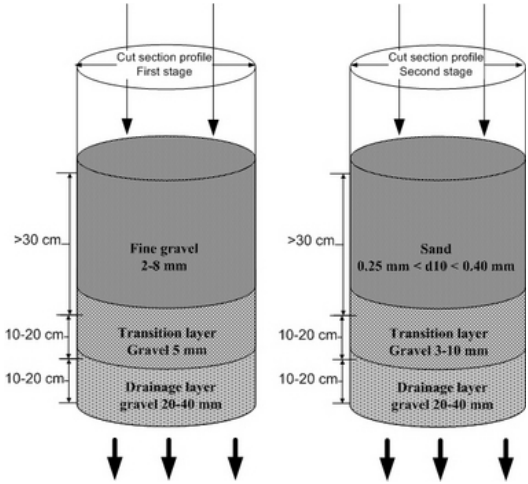

Figure 2.3: Schematic of the substrate profile in each treatment stage

According to its treatment performance, the system is very efficient in terms of COD, TSS, and nitrification (Boutin et al. 1997). The sludge withdrawal should be performed approximately once every 10-15 years, and this has no subsequent effect to the regrowth of reeds from the rhizomes. One particular plant in Roussillon, which was designed for approximately 1250 PE, has the total area of 1550 m^2. The system has exhibited very good treatment performance. The average effluent concentration of BOD during the 3 years operation was approximately 6 mg/L, as well as around 5 and 2 mg/L of Kjeldahl nitrogen and ammonium nitrogen, respectively (Liénard and Boutin 2003). Nevertheless, the effluent nitrate concentration remains the prime concern if one aims for total nitrogen removal. This is generally the case in 2-stages VSFCWs due to the lack of denitrification. Another system based on this principle in France shows a considerable amount of nitrate in the final effluent from 20 treatment plants varying between 14 and 84 mg/L with a mean value of 43 mg/L (Paing and Voisin 2005). The treatment performance can be considered comparable to the system in Roussillon.

With this system, no septic tank is required. As a result, the construction cost of septic tank can be neglected, and the potential associated health risks for human and groundwater contamination can be avoided. Photo from one of the plants in France is shown in figure 2.4.

Figure 2.4: Photo of the French first-stage VSFCWs in Evieu, France

3 Overview of the vermicomposting process

3.1 Background

Vermicomposting principally utilizes the use of earthworms to ingest organic matter and egest a nutrient-rich cast that can be used as a soil conditioner. After fragmentation and ingestion, the microbial activity for the decomposition process is enhanced (Atiyeh et al. 2000). The process was also studied, revealing the changes in the composition properties of the wastes during vermicomposting (Kalinina et al. 2002). Advantages of this technology are that it can enhance, speed up, and assist the composting process as well as the quality of the end product. In addition, vermicomposting is considered to be odour-free because earthworms release coelomic fluids in the decaying waste biomass which has anti-bacterial properties (Sinha et al. 2002). Pathogens are also killed according to this effect.

In terms of pathogen reduction, there have been several works outlining the great reduction of pathogenic microorganisms by vermicomposting (Dominguez et al. 1997, Edwards 2004, Vigueros and Camperos 2002). This technology is capable of reducing pathogens which are problematic and pose serious concern in terms of waste treatment. Particular study also demonstrated that earthworms can reduce the U.S. Environmental Protection Agency (USEPA) pathogen indicators in biosolids in as short a time as 144 hours (Eastman et al. 2001). This reduction greatly exceeds the required USEPA three-to four-fold reduction within 144 hours necessarily for classifying vermicomposting process as a Class A stabilization method (average six-fold reduction (98.70%) of faecal coliforms from 8.5 billion MPN/g within 24 hours with a continual reduction). In practical operation, it was reported by vermiculturists that plant or human pathogens have never been a problem during their operations (Riggle and Holmes 1994).

There are also comparative differences between normal composting and vermicomposting process that shall be mentioned. Composting is performed through thermophilic stage (45 to 65°C). However, it is a mesophilic stage (20 to 38°C) that prevails in vermicomposting. Moreover, the types of microbial communities that are predominant during the process are also different. Thermophilic bacteria, fungi and actinomycetes are the main actors in composting, whereas earthworms and mesophilic microorganisms predominate in vermicomposting (Dominguez et al. 1997).

Compared with ordinary soil, the worm casts, or so-called vermicompost, contain five times more nitrogen, seven times more phosphorus and 11 times more potassium (Cochran 2002): they lie in the forms that are readily taken up by the plants. Its structure is finely divided peat-like materials with high porosity, surface area, drainage, and water-holding capacity (Edwards and Burrows 1988). Therefore, the vermicompost products should theoretically enhance and improve the growth of plant when they are added into the soil. As they are rich in humic acids, they can also greatly improve the structure of the soil. Compared with normal compost, vermicompost from animal manure is better at enriching humus due to more free humic acids. Moreover, its structure is considered as water-stable with a predominance of agronomically valuable fractions which poses higher content than normal compost (Kalinina et al. 2002). The differences between normal compost and vermicompost are shown in table 3.1.

Table 3.1: Chemical characteristics of garden compost and vermicompost (modified from Dickerson 1999)

Parameter*	Garden compost[1]	Vermicompost[2]
pH	7.80	6.80
Electrical Conductivity (EC) (mmhos/cm)	3.60	11.70
Total Kjeldahl nitrogen (TKN)	0.80	1.94
Nitrate nitrogen (ppm)	156.60	902.20
Phosphorous (%)	0.35	0.47
Potassium (%)	0.48	0.70
Sodium (%)	<0.01	0.02
Magnesium (%)	0.57	0.46
Iron (ppm)	11690	7563
Zinc (ppm)	128	278
Manganese (ppm)	414	475
Copper (ppm)	17	27
Boron (ppm)	25	34
Aluminium (ppm)	7380	7012

[1]Albuquerque sample [2]Tijeras sample

* Units: ppm = parts per million mmhos/cm = millimhos per centimeter

In terms of practical studies involving the use of vermicompost for agricultural purposes, it was demonstrated that growth of tomato was significantly enhanced with increasing concentration of vermicompost from pig manure (Atiyeh et al. 2000). Wheat also achieved higher dry weights after being amended with vermicompost from organic waste than normal compost or synthetic fertilizer. This is due to the fact that rate of nitrogen release is more synchronized with plants' needs (Chaoui 2000). Moreover, vermicompost could be sold for the price up to three times more than most normal compost (Riggle and Holmes 1994). It should be noted that the characteristic of vermicompost would apparently vary depending on the characteristic of parent material (Edwards 2004). The nutrient contents among different types of wastes are provided in table 3.2.

Table 3.2: Comparison of the nutrient contents among different types of wastes (modified from Gotaas 1956)

Manure	%Nitrogen	% Phosphorous	% Potassium
Human	5-7	3-5.4	1.0-2.5
Cattle	1.67	1.11	0.56
Pig	3.75	1.87	1.25
Poultry	6.27	5.92	3.27
Sewage	5-10	2.5-4.5	3.0-4.5

Apart from its role as plant growth promoter and soil conditioner, vermicompost can also be used to control disease such as fungus problems in plant, to repel insect such as ants, and to eliminate odors within hours when 10% of earthworm cast is mixed with composted animal manure (Hahn 2000).

3.2 Earthworms and their roles

Although there are almost 4000 described earthworms worldwide, detailed ecological studies have been made on fewer than 20 of these. Earthworms can be classified as detrivores and geophages according to their feeding habit (Lee 1985). Detrivores feed on plant litter or dead roots and other plant debris as well as on mammalian dung. These earthworms are called humus formers and they include the epigeic and anecic earthworms. Some examples include *Perionyx excavatus*, *Eisenia fetida*, *Eudrilus* *euginae*, and *Polypheretima elongate* (Ismail 1997). Geophagous worms influent mostly on the aeration and mixing of subsoil, by which they comprise the endogeic earthworms. Both types have been simply named based on their role, either as composters for detrivores or fieldworkers for geophages (Buckerfield 1994).

Epigeic earthworms such as *Eisenia fetida* live mainly in the soil surface consuming the organic matter on the top soil. Endogeic earthworms reside deeper than the first group. Anecic earthworms, e.g. *Lumbricus terrestris*, predominantly make even deeper vertical burrows. In general, only epigeic and anecic earthworms have been used in the vermicomposting process as they associate with free living soil bacteria to constitute the drilosphere and organic matter was primarily their feed (Ismail 1995). Figure 3.1 illustrates their burrowing patterns among these three types.

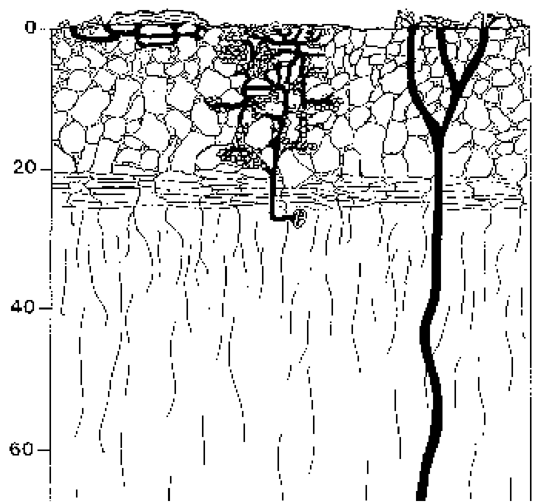

Figure 3.1: Burrowing patterns of epigeic (left), endogeic (middle), and anecic (right) earthworms (The New Zealand Institute for Crop & Food Research Limited)

The species widely used in vermicomposting process are *Eisenia fetida* (tiger worm), *Eisenia andrei* (red tiger worm), *Perionyx excavatus* (indian blue), *Eudrilus eugeniae* (African nightcrawler), *Eisenia veneta* (European nightcrawler), and so on (Edwards 2004). In Thailand, the local species used in vermicomposting process are *Pheretima* *peguana* and *Pheretima posthuma* (Julian et al. 1999). Recently, there has been an import of *Eisenia fetida* into Thailand for vermicomposting purpose (Trakullertsathien C. 2003). General features of some species are illustrated below (Blakemore 2000, Gates 1972);

Eisenia fetida: (length 35-120 mm, width 3-6 mm)

- Behavior: If agitated, ejects yellow coelomic fluid with distinctive nutty smell
- Color: variable, from light pink to deep chestnut brown dorsally, buff ventrally, iridescent

Perionyx excavatus: (length 30-180 mm, width 2.5-7 mm)

- Behavior: Moves rapidly to escape handling and exudes colemic fluid, sometimes tail autonomy occurs
- Color: Anterior dorsum violet-red with blue iridescence

Eudrilus eugeniae: (length 90-165 mm, width 4-8 mm)

- Behavior: Active with rapid escape response, if captured become very placid and can be readily handled
- Color: Red-brown dorsum, anterior bright blue/green iridescent

Pheretima peguana (length 140-240 mm, width 5-8 mm)

- Behavior: In the soil of gardens, lawns, banana groves, and numerous other sites in the cities
- Color: reddish, in circular muscle layer.

The life cycles of the European *Eisenia fetida* and the Thai *Pheretima peguana* are illustrated below.

Table 3.3: Cycles of selected earthworms species (Tancho 2005, Venter and Reinecke 1988)

Cycle	***Eisenia fetida***	***Pheretima peguana***
Hatchling	±3 per cocoon	±10 per cocoon
Maturing (citellum development)	40-60 days	150-180 days
Formation of cocoon after mating	≈ 4 days	Data not available
Incubation period before hatchling of cocoon	≈ 23 days	25-30 days

Several key issues need to be controlled in order to achieve maximum productivity of vermicompost and earthworm growth. Among them are maintaining aerobic condition, optimal moisture, and temperature condition. Moreover, earthworms cannot tolerate an excessive amount of ammonia and salts (Edwards 2004). There have been several works that confirmed these statements based on the high ammonia content of several types in organic wastes treated by vermicomposting (Gunadi and Edwards 2003, Gunadi et al. 2003). Generally, 1 kg of food waste required approximately 2 kg of earthworms (approximately 4000 breeders) to attain vermicomposting process in 24 hours, with around 0.24 m^3 volume of processing chamber is needed in accordance with this quantity of earthworms (Dickerson 1999).

An importation of extraneous species is often considered unnecessary and dangerous as their subsequent effects on bioinvasion into the ecosystem have not been widely studied (Frelich et al. 2006). It is recommended to select native or locally available species for the vermicomposting process. The adaptation of earthworms to local surrounding is also an issue. In terms of optimal operating condition, their tolerance to each particular climate is different.

Generally, the most applied species for breaking down of wastes in the temperate climatic regions is *Eisenia fetida.* This is due to several reasons; earthworms belonging to this species are the most commonly used in today's vermicomposting process, they can tolerate high population density pressure, they have a wide temperature tolerance, and they can live in organic wastes with a range of moisture content. Moreover, they are tough worms, readily-handled, and ubiquitous (Edwards 2004). However, this species may not be available locally and may not be suited to some regions since they are only native in temperate regions as stated previously.

Species such as *Perionyx excavatus* and *Eudrilus eugeniae* are more common in warmer climates. They would be more suitable for the vermicomposting process in those regions. For instance, in Africa it is recommended to use *Eudrilus eugeniae*, which can reach sexual maturity in as little as five weeks compared with *E. fetida* which requires 6-8 weeks (Edwards and Burrows 1988) and *Perionyx excavatus* in Asia as they are widely distributed. Both of these species are most productive at 25°C, which is higher than the optimal temperature quoted for other species in temperate regions (Dominguez et al. 2001).

For the case of Thailand, the species commonly used is *Pheretima peguana*. The tolerance under different temperatures varies considerably for each species, whereas their optimum moisture requirements, C:N ratio, and ammonia content do not vary greatly (Edwards 2004). The temperature tolerance for some species as well as their distribution are described and compared in table 3.4.

Table 3.4: Comparison of some vermicomposting earthworm species in terms of the optimal and tolerable temperature ranges (Blakemore 2000, Dominguez et al. 2001, Edwards 2004)

Species	Temperature ranges (˚C)		Distribution
	Tolerated	Optimum	
Eisenia fetida	0-35	20-25	Temperate regions
Eudrilus eugeniae	9-30	20-28	Africa, India, North and South America
Perionyx excavatus	9-30	15-30	Asia and Australia
Eisenia veneta	3-33	15-25	Europe

3.3 Why earthworms would fit into the constructed wetlands

As no prior study has conducted this kind of experiment, it is worth investigating based on literature whether earthworms can be added, and consequently thrive in the constructed wetlands. In principle, earthworms prefer an aerobic condition (Edwards 2004). Therefore, this should be applicable for the VSFCWs due to intermittent feeding rather than the anaerobically-operated HSFCWs. VSFCWs could offer a viable habitat for earthworm populations because of their ability to transfer oxygen to the root zone. This ability creates the aerobic micro-sites within the largely anoxic environment (Brix 1997). Under anoxic conditions, the earthworms will die.

The organic in wastewater can serve as their natural food source, especially when the prior studies with respect to the success regarding vermicomposting of several types of organic wastes are considered. Moreover, the neutral pH environment in the wetland media also provides them a suitable environment concerning the optimal pH issue. A moist characteristic within the SFCWs associated with the supply of wastewater means that there would be no risk of the death of earthworms due to lack of moisture content. In terms of vermicomposting organic wastes, the optimal conditions for the earthworms can be seen in table 3.5. Although it represents only one species, it is worth noting that most species principally share the common range from these values according to the reasons stated in the previous section, except the temperature. The optimum range for tropical species would normally be higher, for example up to 28°C for *Eudrilus eugeniae*, an African species (Dominguez et al. 2001). Therefore, it is preferable to apply the native species due to their adaptability under each local temperature.

Table 3.5: Optimal conditions for breeding earthworms (*E. fetida*) in animal and vegetable wastes (modified after Edwards 2004)

Condition	Requirements
Moisture content	80-90% (limits 60-90%)
Oxygen requirement	Aerobic condition
Lighting condition	darkness
Temperature	20-25°C (0-35°C tolerated) (Blakemore 2000)
Ammonia content of waste	Low: <0.5 mg/g
Salt content of waste	Low: <0.5%
pH	>5 and <9
C:N ratio	25:1 (Ndegwa and Thompson 2000)

According to this table, the wetland environment complies with several constraints for the endurance of earthworms. Only the parameters dependent on the type and characteristic of wastewater are of concern. However, it should be noted that the value presented in this table is based on the criteria of earthworms living directly within the waste as a substrate, not within the sand or gravel as a substrate. Therefore, earthworms might be able to sustain a higher load of ammonia and salt within the SFCWs. Nevertheless, there might be some concerns regarding the issue of temperature: earthworms generally prefer the indoor temperature range and they might not be able to sustain an outdoor temperature if presented in constructed wetlands. Regarding this point, the plants and depth could alleviate the extreme temperature condition including the direct sunlight effect which is detrimental to earthworms. As a result, there is high probability that earthworms can thrive within the constructed wetlands.

Still, their relative potential benefits with respect to the reduction of clogging as well as the treatment performance remain to be explored. Concerning the latter benefit, earthworms might also improve the treatment efficiency because they and aerobic microbes can act symbiotically to accelerate and enhance the decomposition of the organic matter (Loehr et al. 1988).

4 Materials and methods

4.1 Determination of alternative plants to be used in constructed wetlands

In this study, a well-known climate classification system according to Koeppen was used (Geiger 1961). However, as the classification is very complicated, a simplification is necessary in order to determine suitable plants that possess high resource recovery potentials according to each climatic region. Concerning the criteria used in this determination, as energy is considered one of the most serious issues nowadays, it is separated from the utilization options and is presented on its own as one of the consideration criteria.

Still, the main purpose of constructed wetlands is to treat wastewater. Not all plant species that pose a high productivity or have other ancillary benefits are able to tolerate the hydraulic and highly-loaded organic and eutrophic conditions typically found in constructed wetlands. Finally, the costs to obtain such plants should not be overlooked. As a result, 5 criteria namely 1) potentials for energy sources, 2) plants utilization options, 3) nutrient uptake, in which all these three were directly related to the resource recovery aspect, 4) treatment performance and tolerance to inundation as well as the components in municipal wastewater, and 5) costs of plants were included in this analysis. In total, 44 species of plants were investigated based on hundreds of literature. The most suitable plants were proposed according to their availabilities in each climate zone, as generally temperate plants might not present in tropical climate.

4.1.1 Investigated species in alphabetical order

Arundo donax (giant reed), *Baumea articulata* (jointed twig-rush), *Canna flaccida* (canna lily), *Canna indica* (Indian shot), *Carex acuta* (slender tufted sedge), *Carex aquatilis* (water sedge), *Carex fascicularis* (tassel sedge), *Carex rostrata* (beaked sedge), *Coix lacryma-jobi* (Job’s tears), *Cyperus involucratus* (umbrella sedge), *Cyperus latifolius* (broad-leaved sedge), *Cyperus malaccensis* (Shichito matgrass), *Cyperus papyrus* (papyrus), *Eleocharis sphacelata* (tall spike rush), *Glyceria maxima* (reed sweet grass), *Juncus effusus* (soft rush), *Juncus ingens* (giant rush), *Lepironia articulata* (tube sedge), *Lolium perenne* (perennial ryegrass), *Miscanthus* *sacchariflorus* (Amur silver grass), *Miscanthidium violaceum* (Miscanthidium), *Pennisetum clandestinum* (Kikuyu grass), *Pennisetum purpureum* (Napier grass), *Phalaris arundinacea* (reed canary grass), *Phragmites karka* (tall reed), *Phragmites mauritianus* (Lowveld reed), *Scirpus acutus* (hard stem bulrush), *Scirpus californicus* (giant bulrush), *Scirpus cyperinus* (wool grass), *Scirpus grossus* (greater club rush), *Scirpus pungens* (Olney's bulrush), *Scirpus validus* (soft stem bulrush), *Scirpus lacustris* (common bulrush), *Scirpus maritimus* (alkali bulrush), *Typha angustifolia* (narrow-leaved cattail), *Typha capensis* (common cattail), *Typha domingensis* (southern cattail), *Typha latifolia* (broad-leaved cattail), *Typha orientalis* (broad-leaved cumbungi), *Typha subulata* (cattail, totora), *Vetiveria zizanioides* (vetiver grass), *Zizaniopsis bonariensis* (Espadaña), *Zizania latifolia* (Manchurian wild rice), *Zizaniopsis miliacea* (giant cutgrass)

4.2 Presences of earthworms within the VSFCWs in Germany

The VSFCW sampling site is located at the Flintenbreite village in Luebeck, Germany. It was 8 years old by the year 2008. They system treats grey water from the settlement. In this so-called "ecovillage", a source separation system of wastewater for the housing estate with inhabitants of 350 was installed. The treatment system consisted of VSFCWs preceded by septic tanks, in which the area for the VSFCW is approximately 2 m^2/PE. Gravel was used as a substrate within the system. In terms of performance, it is effective in reducing organic and nitrogen, but not in the case of phosphorus. Performance of the system is shown in table 4.1.

Table 4.1: Concentration of greywater before entering and after leaving the VSFCWs (GTZ ecosan team and Oldenburg 2005)

Parameter	Influent (mg/L)	Effluent (mg/L)
COD	502	59
BOD	194	14
Total N	12	2.7
NH_4-N	4.5	0.9
TP	8	5.7
PO_4-P	7.6	4.8

In total, 4 samplings dates were made over a time span of almost 2 years, from 13.06.2006 to 06.03.2008. The sampling was arranged at different seasons. It was undertaken on 13.06.2006, 13.11.2006, 27.04.2007, and 13.07.2007. Each was performed in the afternoon by earthworm extraction method with hot mustard powder (Fox 2006) so that the plants and substrates of VSFCWs were not destroyed. This method is widely practiced and more preferred to manual digging as well as the extraction using formalin. Apart from it being non-disruptive to the soil, the time and labor required for sampling can be saved. Its effectiveness was also outlined by several works (Lawrence and Bowers 2002, Muramoto and Werner 2002). Nevertheless, in order to confirm the consistency of this method, manual digging for the selected surface area of 0.2 m^2 and up to the depth of 0.15 m was applied only on the 13.06.2006 sampling date.

The mustard powder solution is prepared by mixing approximately 4 L of tap water with 40 g of yellow mustard powder that can be bought from any groceries. The solution is prepared at least 1 day prior to the sampling date so that the mustard could develop the spiciness. Generally, this mustard solution works by irritating the skin of earthworms. As a result, they need to move to the surface and consequently the sampling can be made.

At the sampling site, dry litters or fallen leaves are firstly removed before putting a frame with a dimension of 30 cm x 30 cm over the surface of the constructed wetlands. The prepared solution is then sprinkled evenly and slowly over the entire sample plot. Earthworms would be driven onto the surface within 5-10 minutes and their collection is simultaneously undertaken by a forceps. A particular photo taken during one of the sampling dates is shown in figure 4.1.

Figure 4.1: Pouring of the mustard powder solution over the surface of the constructed wetlands

4.3 Experiment in Germany with raw wastewater

As the combination of earthworms and constructed wetlands has never been implemented before, it was considered worthwhile to firstly set up the experiment in a lab-scale study, and further extend to a pilot-scale study. After preliminary results were obtained, the decision can be evaluated in order to effectively design the experiment.

4.3.1 Lab-scale experiments

The preliminary study using a lab-scale experiment has been set-up consisting of 4 small-scale cylinders with a 10 cm diameter located inside the 20°C temperature-controlled chamber. According to the prior study within the institute concerning vermicomposting of faecal matter (Shalabi 2006), it was found that *E. fetida* could not survive 30°C temperatures after a couple of days. Comparable results can be obtained from the experiments conducted at 20°C and 25°C, in which earthworms could survive under both conditions. Therefore, the study was implemented at the 20°C temperature to ascertain that external summer effect has no effect on the preliminary results. The gravel is layered as shown in figure 4.2 and is operated according to the vertical subsurface-flow principle. Domestic wastewater was taken from the sewer underneath the vicinity of Hamburg University of Technology (TUHH) in the area called Harburg.

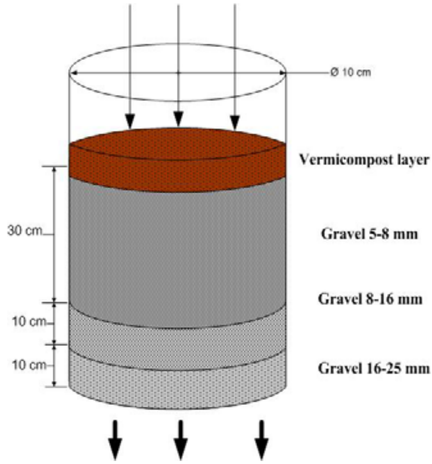

Figure 4.2: Schematic of the lab-scale mesocosms

The reference HLR at 8 cm/d is selected for the first set as this is the maximum value recommended in the German guideline for VSFCWs for the treatment of municipal wastewater (ATV-DVWK 2004). As the objective was to determine the clogging potential, the HLR value for another set of mesocosms was 12 cm/d. The incubation of every mesocosms was undertaken for 3 weeks in prior to the beginning of the experiment, by feeding tap water during the first week and wastewater during the following weeks. After that, 5 g of native European earthworms, a species called *Eisenia Fetida*, were added into one mesocosm for each set, the other mesocosm was then operated without earthworm. In this case, 5 g of earthworms approximately equal to 10-12 individuals. This operational set-up is labeled, simplified, and presented in table 4.2. Every reactor was fed once a day at the same period except on Sunday. The experiment was allowed to run for 2 months, from June 2006 until July 2006. Sampling was carried out every 3 days, and analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA et al. 1998). The parameters consisted of SS, pH, BOD_5, TOC, TN, NH_4^+, NO_3, and TP. The survival rate of earthworms was evaluated at the end of the experiment by hand counting the number as well as by weighing. During the study period, observation of clogging potential was also carried out as to whether the flow rate into the reactor was reduced after each feeding. It can be stated that clogging occurs when the flow of wastewater into the microcosms appears to be slower.

Table 4.2: Operational set-up for the lab-scale experiment

	Mesocosm number			
	1	**2**	**3**	**4**
HLR (cm/d)	8	12	8	12
Quantity of earthworms added (g)	No	No	5	5

4.3.2 Pilot-scale experiments

In this experiment, data obtained during the lab-scale study was also used in order to appropriately design the system. One example worth outlining here was the finer size of gravel, which was lowered from 5-8 to 2-8 mm as no clogging appeared during the lab-scale experiments. Moreover, the size reduction could lead to an improvement of the efficiency. There were 3 reactors made of Plexiglas with a diameter of 30 cm, a planted one with earthworms, a planted one without earthworms, and an unplanted one with earthworms. The design was mainly based on the 1st-stage French VSFCWs so that the results can be compared with other established systems to some extent. Nonetheless, the operating condition in this study was considered more extreme, such as no resting period. By these 3 configurations, one could compare the potentials of applying earthworms into VSFCWs as well as applying earthworms into the substrates alone, i.e. without plants. The photo of three VSFCWs is shown in figure 4.3.

Figure 4.3: Photo showing the pilot-scale VSFCWs experiments in Germany

The substrate gradient inside each VSFCW is illustrated in figure 4.4. Domestic wastewater was pumped directly from the sewer underneath the Harburg area in Hamburg into the storage tank and fed into each of the mesocosm under the HLR of 12 cm/d. The frequency of each feed was set at 10 times per day. Earthworms were added into one planted reactor (labeled as P1) as well as into one unplanted reactor (labeled as P3). The reactor number P2 were operated without any addition of earthworms. The schematic illustrated below also corresponded with the photo shown in figure 4.3. The aluminum foils were used to coat the outer surface of all VSFCWs in order to prevent the effect of direct sunlight, which could lead to an unexpected eutrophication of the substrates located around the side surface of VSFCWs.

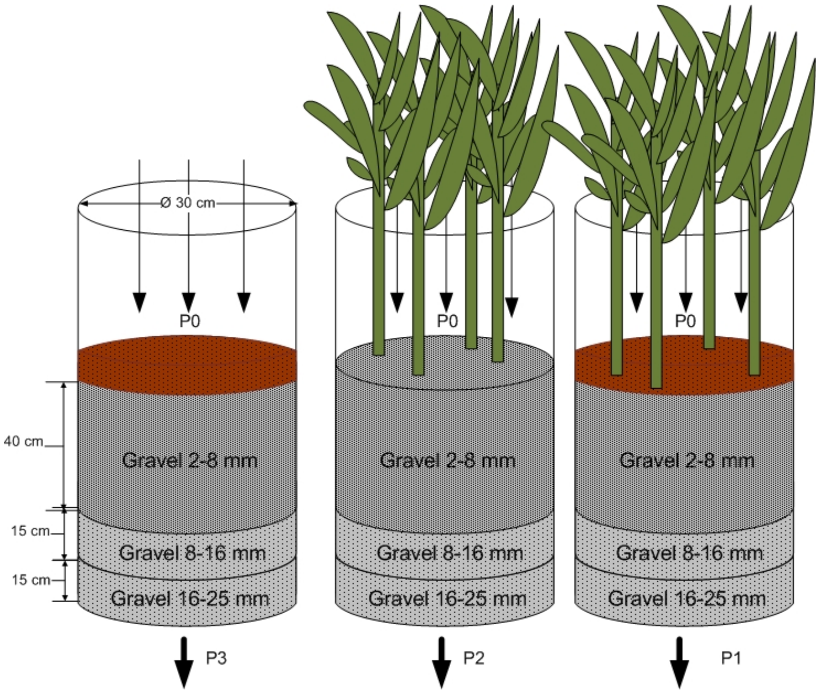

Figure 4.4: Schematic of the pilot-scale VSFCWs in Germany

Common reed *(Phragmites Australis)* was planted in P1 and P2 for 3 months in prior to the first sampling to ensure that the beds were fully vegetated. European earthworm species, *Eisenia fetida*, were manually introduced over the surface of P1 and P3 for 25

g. Sampling was carried out every two weeks and similar analyses to the lab-scale experiments, both in terms of methods and parameters, were performed. In addition, clogging potential was also observed by simply monitoring the inflow rate into the VSFCWs. Clogging occurs when the flow of wastewater into the microcosms appears to be slower. The experiment was allowed to run from June to October 2007, totally over a period of 5 months in order to confirm the potentials of this concept under a long-term condition. After that, the system was allowed to rest for a month. The second trial was conducted for another 5 months during a period between January and May 2008. Prior to beginning both trials, the VSFCWs were inoculated with domestic wastewater for a month so that microbial communities within the systems could be established. No analysis was made during this period. Average results with respect to each parameter were presented.

4.4 Experiment in Thailand with swine wastewater

Similar to the study in Germany, the experiment in Thailand was firstly conducted as a lab-scale experiment. Further scale-up to the pilot-scale study was implemented after some results were obtained. Due to the extreme concentration of swine wastewater in comparison with the domestic wastewater especially with respect to clogging-related substances and ammonia content, preliminary experiments were undertaken in prior to beginning the lab-scale study.

4.4.1 Preliminary experiments

The experiment was set up by using 6 small-scale reactors made of transparent plastic (10 cm diameter and 20 cm height), with the gravel size of, from top to bottom, 5-25 mm diameter for 10 cm height, and 25-40 mm diameter for 2 cm height as a drainage layer. The swine wastewater was taken from Swine Research Unit Farm, Department of Animal Husbandry, Faculty of Veterinary Science, Chulalongkorn University, Nakornpathom province. It was diluted with deionized water to get a ratio of 1:1, 1:2, and 1:4, in order to observe the maximum threshold level that earthworms can thrive. To make a comparison, there were 2 sets of reactors for each dilution, one with 20 individuals of earthworm (corresponding to around 5 g) and one without.

Generally, the use of local earthworms species has been highly encouraged due to several reasons; 1) they have more tolerance to local climatic condition, 2) the use of foreign (imported) species could cause an disruptive impact to the ecological system (Edwards 2004), and 3) they are easier to find and cheaper to obtain. In this experiment, *Pheretima peguana* was used. Photo of this species is shown in figure 4.5. This species is local and has been proven to be able to vermicompost organic waste in Thailand (Julian et al. 1999). Due to the time constraint, all of the reactors were unplanted.

Figure 4.5: Earthworms species *Pheretima Peguana*

The HLR was set at 8 cm/d instead of 12 cm/d applied for the study in Germany. Because of the extremely high solid content in swine wastewater, this rate could still be regarded as an extreme case. The reactors were fed twice a day, with an interval of 6 hours in between. The experiment was run for 10 days during December 2006. The samples were taken every 2 days. Analyses were conducted for the average results concerning the removal of COD, NH_4, NO_3, TSS, TDS, and TS. Nevertheless, they served only as a supplement for further designing the lab-scale experiment. In this study, the major objective was to investigate the survivability of earthworms as well as their potential to reduce clogging.

The survival rate of earthworms was evaluated at the end of the experiment by hand counting the number as well as by weighing. Clogging potential was studied in both experiments by simply observing whether the flow rate into the reactor was reduced after each feeding. Clogging occurs when the flow of wastewater into the microcosms appears to be slower.

4.4.2 Lab-scale experiments

The lab-scale reactors were assembled and labeled according to figure 4.6, in which there were two configurations of the system: 1) VSFCWs followed by HSFCWs, 2) two-stages VSFCWs. The 1st-stage VSFCWs had a diameter of 25 cm with 35 cm depth containing different sizes of gravel (25 cm of 1-5 mm gravel, followed by 5 cm of 5-15 mm gravel, and finally 5 cm of 15-25 mm drainage gravel at the bottom). The 2nd-stage VSFCWs had diameter of 27 cm, with 35 cm depth containing sand and gravel (from top to bottom, 10 cm of 0.5-0.8 mm sand, followed by 15 cm of 1-5 mm gravel, 5 cm of 5-15 mm gravel, and finally 5 cm of 15-25 mm drainage gravel). The HSFCWs had a depth of 30 cm, a width of 39 cm, a length of 58 cm, and contained 2-3 mm gravel. Image of the experimental-setup is shown in figure 4.7.

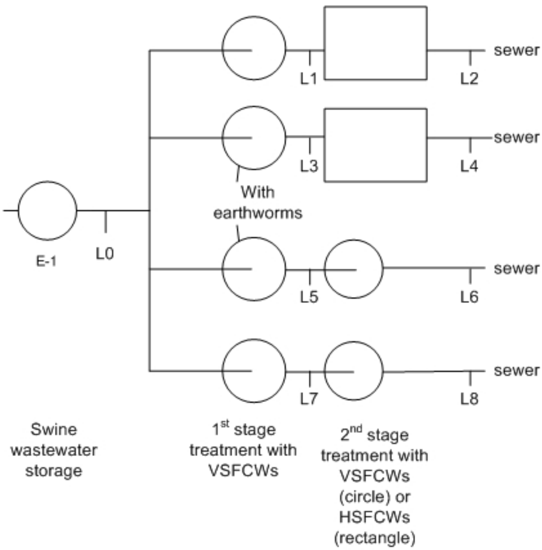

Figure 4.6: Illustration of the lab-scale constructed wetlands configuration

Figure 4.7: Photo showing the lab-scale swine wastewater treatment configuration in Thailand

For each of the two configurations, 25 g of *Pheretima peguana* were added into one of the 1st-stage reactor whereas another one served as a control, meaning without an addition of earthworms, for comparison purpose. Swine wastewater was taken from the Swine Research Unit farm, Department of Animal Husbandry, Faculty of Veterinary Science, Chulalongkorn University, Nakornpathom province. It was fed into each of the 1st-stage reactor 6 times a day at the HLR of 8 cm/d. Regular feeding was carried out for a month in order to incubate the microbiological communities within the system for an effective treatment. Samplings and analyses were conducted once every month and the average results concerning the removal of BOD, COD, TKN, TSS, TVSS, and TS during the 6-months study period were presented.

4.4.3 Pilot-scale experiments

The pilot-scale SFCWs were assembled during the period between December 2007 and January 2008. Each sampling point was labeled according to figure 4.8. Two units with a similar configuration, i.e. 2-stages SFCWs with VSFCWs as a 1st-stage unit followed by HSFCWs as a 2nd-stage unit, were constructed. Earthworms were added into one of the 1st-stage VSFCWs, labeled with W. All the units were planted with the local narrow-leaved cattail (*Typha angustifolia)* for half a year in prior to undertaking the real experiment to ensure that the bed was fully vegetated. The final effluent was released into the nearby pond.

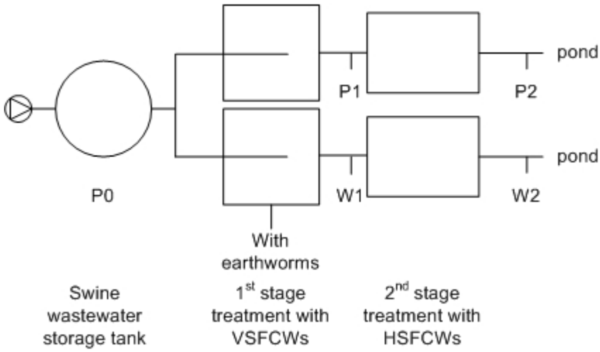

Figure 4.8: The configuration of the pilot-scale SFCWs

In terms of the dimension, the VSFCWs had both the length and the width of 100 cm with 100 cm depth containing a gradient of different gravel sizes for 70 cm height as illustrated in figure 4.9. For the HSFCWs, its dimension was 90 cm width and 140 cm length containing 2-3 mm gravel for 65 cm depth and 5 cm of free board.

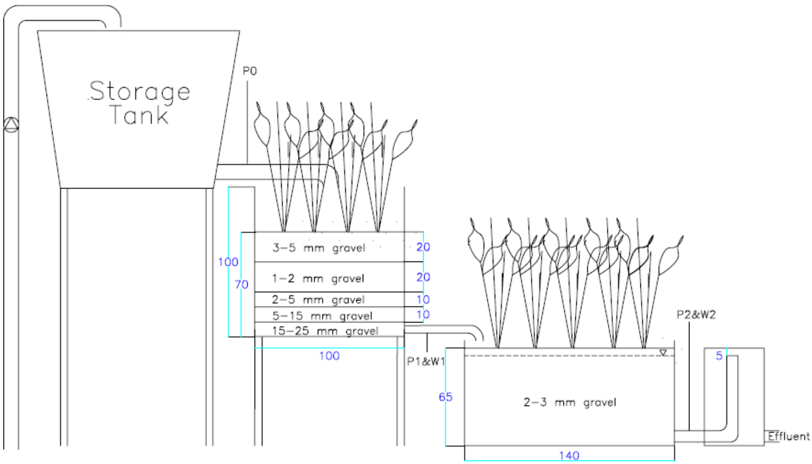

Figure 4.9: Schematic of the pilot-scale constructed wetlands

400 g of *Pheretima peguana* were used in this study. They were added into the VSFCW by manual distribution over the surface. Another unit (labeled P) without earthworms served as a control for comparison purposes. The source of swine

wastewater was from the Swine Research Unit farm at the Department of Animal Husbandry, Faculty of Veterinary Science, Chulalongkorn University, Nakornpathom province. It was pumped directly into the storage tank six times a day. It was then fed into each 1st-stage reactor by means of gravity at a hydraulic loading rate (HLR) of 8 cm/d, which was equivalent to the lab-scale study. Regular feeding with swine wastewater was carried out for a month before the first sampling in order to incubate the microbiological communities within the system for an effective treatment. Samplings and analyses according to the Standard Methods for Water and Wastewater Examination were conducted every three weeks (APHA et al. 1998).

The average results concerning the removal of BOD, COD, TKN, SS, TVSS, and TS, as well as the sludge produced over the surface of the wetlands during the 6-month study period from July to December, 2008 were presented. These parameters were compared to the Thai effluent standard for swine wastewater effluent. Clogging potential was also observed by simply monitoring the infiltration time of the influent. Statistical correlations between the loading rate and the treated load after the 1st-stage beds of BOD and SS were developed and presented. Also, the cattails from all the units were harvested by hand and their corresponding biomass as well as their dry matter was determined. Photo of the system can be seen in figure 4.10.

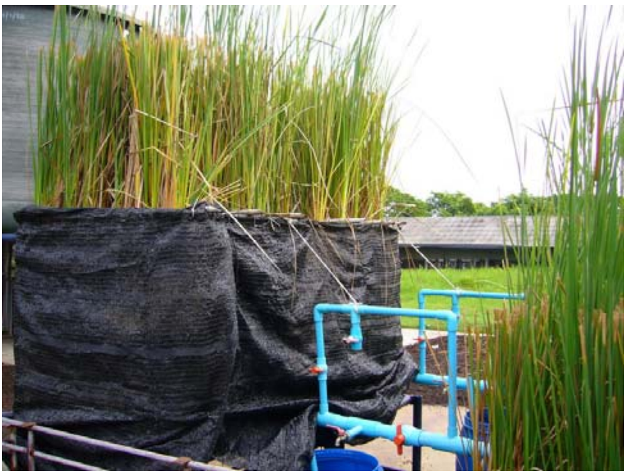

Figure 4.10: Photo showing the pilot-scale swine wastewater treatment system in Thailand

5 Results and discussions

The presentations of the results were divided into 4 parts, in which the structures were outlined similar to the objective and the methodologies stated previously.

5.1 Determination of alternative plants to be used in constructed wetlands

In order to determine the potential alternative plants, climate classification was conducted before making the analysis of each criterion, namely 1) potentials for energy sources, 2) plants utilization options, 3) nutrient uptake, in which all these three were directly related to the resource recovery aspect, 4) treatment performance and tolerance to inundation as well as the components in municipal wastewater, and 5) costs of plants. Finally, the recommendation table was presented.

5.1.1 Classification of climate types

The climate classification map according to Koeppen is illustrated in figure 5.1.

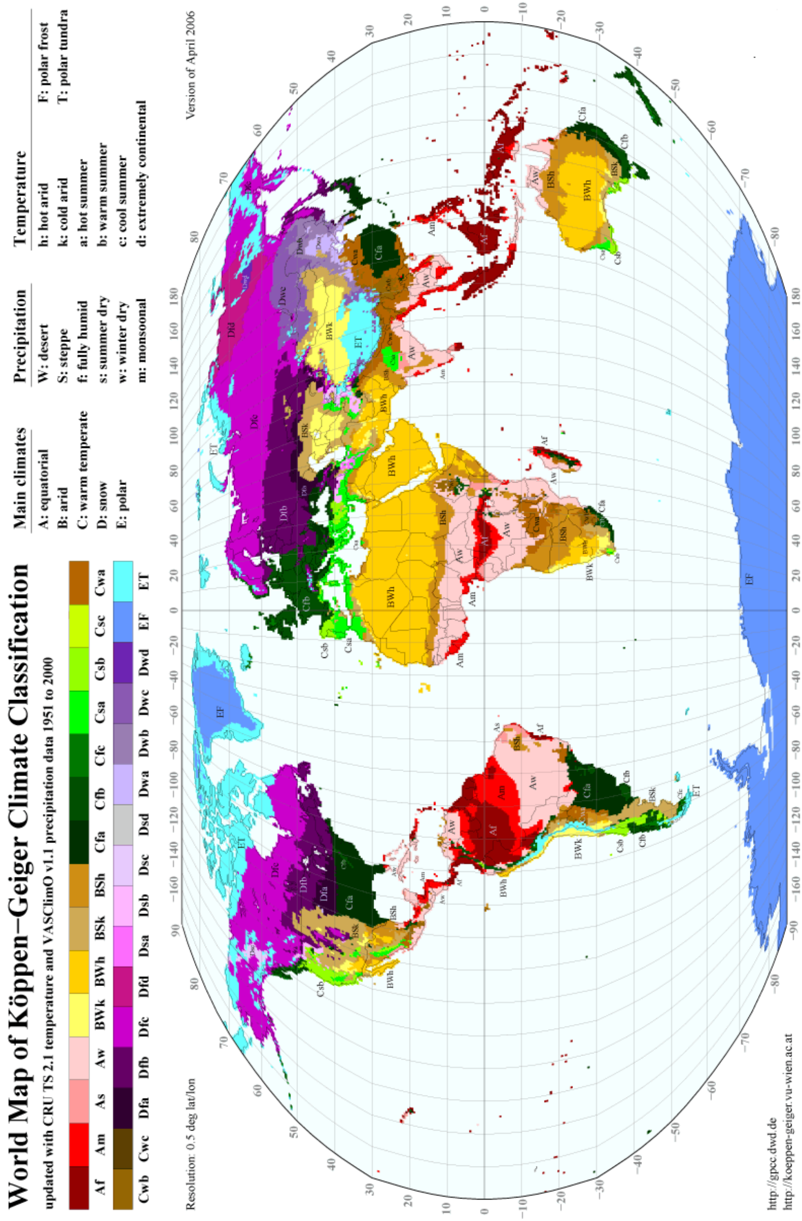

Figure 5.1: Koppen-Geiger climate classification world map (Kottek et al. 2006)

It can be noted from the figure that the map is particularly complex and simplification of the classification was deemed necessary. In this study, the global climatic regions based on Koeppen were divided according to the ranges of latitude, climate characters, and area. As a result, 6 zones were classified and summarized as shown in table 5.1.

Table 5.1: Classification of climate zone (N: North and S: South)

Climate classification	Latitude	Climate characters	Area applied	Abbreviation
Cold/ boreal	50˚-70˚ N/S	Long with very cold winter and short summer Highly varying seasonal temperature Small annual precipitation	Scandinavian Europe Northern parts of North America Northern Asia (e.g. Siberia)	NE NNAm NAs
Temperate	30˚-55˚ N/S (Europe 45˚-60˚N)	Large seasonal changes between summer and winter Highly varying seasonal temperature Abundant precipitation throughout the year	Central and Eastern Europe USA and Southern Canada East Asia New Zealand and Southeast Australia Southern parts of South America South Africa	CEE NAm EAs SAu SSAm SAf
Warm/ Mediterranean	30˚-45˚ N/S	Hot dry summer and mild wet winter Small annual temperature range Small annual precipitation	Southern Europe Western parts of North America (e.g. part of California)	SE WNAm
Subtropical	10˚-30˚ N/S	Seasonal changes between very wet, hot and a dry, cooler period High, tropical temperature during wet season High precipitation during wet season	Eastern North America (e.g. Florida) Central America South and Southeast Asia Central and Southern Africa Northern Australia	ENAm CAm SAs and SEAs CAf NAu

Climate classification	Latitude	Climate characters	Area applied	Abbreviation
Tropical	10˚S-25˚N	No significant seasonal changes in temperature and precipitation High, tropical temperature throughout the year High precipitation and humidity throughout the year	Malay Archipelago (e.g. Indonesia, Singapore) Equatorial Africa (Congo basin) Amazon basin	MAL EqAf SAm
Arid/ desert	10˚-30˚N/S	Extremely dry and hot desert climate Large diurnal variation of temperature Very small annual precipitation	North Africa (Sahara) and Arab Central Australia	Saha CAus

5.1.2 Analysis of each criteria used to determine alternative plants

Potentials for energy sources

The potentials of plants as an energy source were presented based on the extensive investigation of both scientific literature and real case studies. It has been found that, due to the use of biomass as an energy source after harvest, its potential was given mainly based on the productivity and growth rate of the plants in terms of production rates and biomass yields per year. For each level of plants' growth rate, the evaluation was made according to table 5.2.

Plant utilization options

According to this criterion, plants that possess high economical value and/or versatility are better suited for use in SFCWs. This assists stakeholders in choosing the most appropriate utilization option based on the demand for each harvesting season. Among the six utilization options are 1) handicrafts, e.g. weaving materials, basketry, etc., 2) fertilizers, e.g. as composts, 3) animal feed, 4) building and construction materials including insulation and thatching as well as fiber boards, 5) paper making (due to high fiber and cellulose content in their stems), and 6) pharmaceutical products. The evaluation of plant species was rated as follows:

Table 5.2: Criteria rating for the versatility of utilization options as well as the growth rate of plant

Possible utilization options	Versatility	Growth rate of plant	Criteria rating
0 or 1 out of 6	Low	Low	0
2 out of 6	Moderately low	Moderately low	1
3 out of 6	Moderate	Moderate	2
4 out of 6	Moderately high	Moderately high	3
5 out of 6	High	High	4
6 out of 6	Very high	Very high	5

Nutrients uptake

It was reported that the uptake from most of the plants was only minor comparing to other removal mechanisms occurring in SFCWs, which was approximately 8% in terms of nitrogen and 3% in terms of phosphorus based on an average value calculated from several studies (Hurry and Bellinger 1990, Nyakang'o and Van Bruggen 1999, Tanner 1994). As a result, this criterion was considered insignificant and was not needed to be considered for a recommendation table.

Treatment efficiency and tolerance to wastewater

The plants proposed in this study have been demonstrated that they are suitable for use in SFCWs receiving municipal wastewaters. Nevertheless, direct organic removal in the form of BOD or COD by plant uptake is considered non-existence or can even be neglected (Kadlec et al. 2000). In terms of tolerance to wastewater, it can be stated that all the plant species were suitable for the treatment of municipal wastewaters; however the exact ranges cannot be given for most plants due to the wide research differences between the investigated case studies.

Cost of plants

The costs of purchasing the plant propagules, primarily seeds and seedlings, were investigated. Price lists from several countries were analyzed and it was revealed that the cost differences between different species are marginal, and thus cannot be considered as a significant selection criteria. In order to support this argument, selected prices of wetland species from four companies in four different countries and continents are presented in table 5.3.

Table 5.3: Prices of plant seeds from selected countries

Species	Generic name	USA * (US $)	Australia ** (AUD $)	New Zealand *** (NZD)	Germany **** (EUR)
Baumea articulata	Jointed twig-rush	-	6.00	1.80	-
Eleocharis sphacelata	Tall spike rush	-	5.50	2.0	-
Juncus effusus	Soft rush	1.05	6.50	1.8	2.20
Phragmites Australis	Common reed	-	5.50	-	2.00
Scirpus pungens	Olney's bulrush	1.05	5.50	-	-
Scirpus validus	Soft stem bulrush	-	5.50	1.6	-
Typha angustifolia	Narrow-leaved cattail	1.05	-	-	2.20
Typha latifolia	Broad-leaved cattail	1.05	-	-	2.20
Typha orientalis	Broad-leaved cumbungi	-	6.00	2.0	-

* Environmental Concern Inc., St. Michaels, Maryland, USA, 2008

** Watergarden Paradise Aquatic Nursery, Sydney, NSW, Australia, 2008

*** Koanga Gardens Ltd., Maungaturoto, New Zealand, 2005

**** Stauden Junge, Hameln, Germany, 2008

The price was reported without any currency correction to make it simpler for the readers from each country to follow. The data showed that the cost differences between plant propagules were in most cases very marginal although some rare exceptions such as *Juncus effusus* in Australia might be also possible. It should be noted that apart from the selected price list, most of the collected data exhibited similar trends concerning the cost differences between the different wetland plants. Therefore, costs in this case should be of less concern than other criteria. Moreover, it was clear from this data that it was difficult to find the plants available worldwide, let alone locally.

5.1.3 Presentation of the recommendation table

The idea behind the recommendation table was to assist the decision makers while choosing the suitable plants during the planning phase. Based on 44 different plants under investigation, there were 13 species that scored at least 7 out of the maximum 10 points according to both versatility and productivity. The recommendation table of suitable alternative plants was proposed based on each climate zone. The results are shown in table 5.4.

Table 5.4: Recommended alternative plant species in SFCWs according to each climate zone

Climate zone	Recommended Species	Generic name	Versatility rating	Productivity / growth rate	Regions that are generally available
Cold	*Glyceria maxima*	Reed sweet grass	4	4	NE
	Phalaris arundinacea	Reed canary grass	4	3	NE
	Scirpus validus	Soft stem bulrush	3	4	NNAm
Temperate	*Glyceria maxima*	Reed sweet grass	4	3	CEE
	Miscanthus sacchariflorus	Amur silver grass	4	3	EAs
	Phalaris arundinacea	Reed canary grass	5	2	CEE
	Scirpus californicus	Giant bulrush	5	3	NAm, SSAm
	Scirpus lacustris	Common bulrush	3	4	CEE, SAf
	Scirpus validus	Soft stem bulrush	3	4	NAm, SAu
	Zizania latifolia	Manchurian wild rice	4	3	EAs
Warm	*Arundo donax*	Giant reed	5	4	SE
	Scirpus californicus	Giant bulrush	4	3	WNAm
Subtropical	*Arundo donax*	Giant reed	5	4	SAs
	Coix lacryma-jobi	Job's tear	4	3	CAm
	Miscanthus sacchariflorus	Amur silver grass	4	3	SEAs
	Pennisetum purpureum	Napier grass	5	3	SAs, SEAs
	Scirpus grossus	Greater club rush	4	4	SAs, SEAs
	Vetiveria zizanioides	Vetiver grass	5	5	SAs, SEAs, NAu
Tropical	*Cyperus papyrus*	Papyrus	5	4	EqAf
	Pennisetum purpureum	Kikuyu grass	5	3	SAm, SEAs
	Scirpus grossus	Greater club rush	4	4	MAY

No information could be found in the arid desert climate of North Africa (Sahara), Arab, and Central Australia. Therefore, these zones were omitted from the recommendation table. It could also be seen that there were several possibilities under each climate zone that the decision could be based on local availabilities as well as desired choices of utilization options. For example, one of the recommended plants presented in this study that possessed the highest score was vetiver (*Vetiveria zizanioides*), which was found to be a potential plant for resource recovery in Southeast Asia as well as in Northern Australia. In Thailand, this ubiquitous species has also been promoted by H.M. the King of Thailand for treating wastewater. This species possesses a very high versatility rating, and has already been demonstrated in the VSFCWs that the system could achieve the treatment performance comparable to the system planted with conventional wetland species (Kantawanichkul et al. 1999, Chomchalow and Chapman 2003). The dry vetiver leaves can be processed to produce ethanol (Kuhirun and Punnapayak 2000). Hence, for the tropical climate comprising South East Asia, South Asia, and Northern Australia, it was highly recommended to apply this species in the SFCWs.

Apart from all of the plants investigated, a certain bamboo species can also be considered as one of the promising plants to be used for wastewater treatment. It possesses some advantages, such as the ability to be transformed to a valuable product as well as maintaining green foliage year-round (De Vos 2004).

According to the International Network for Bamboo and Rattan (INBAR), bamboos are perennial plants of the grass family (*Poaceae* / *Gramineae*) and comprise over 1,200 species worldwide in more than 100 genera. They are widespread throughout the subtropical and tropical regions worldwide, particularly in South, Southeast and East Asia, as well as in tropical Africa and South America (Brazil). Moreover, they can tolerate the warm/temperate climates such as in the Mediterranean region (De Vos 2000).

Several bamboo species were markedly adaptable plants that tolerated a wide range of climatic conditions. They were usually fast growing and highly productive species and were one of the most widely utilized natural resources in the world. There are several utilization options for bamboo (De Vos 2000, Whish-Wilson 2002), which consist of

- biomass fuel (renewable source of energy),

- timber (wood for furniture or construction material for housing),
- high strength fibre,
- pulp and paper production, and
- livestock forage.

There was one study comparing the treatment efficiency among several conventional species with the unplanted unit as well as one bamboo species *(Bambusa multiplex*) under greenhouse conditions (Wolverton et al. 1983). The unit planted with bamboo performed the poorest in BOD removal compared to all other systems including the unplanted bed. However, the bamboo filter was more effective in the reduction of TKN and ammonia nitrogen than the unvegetated system, but less than three other species. Altogether, it was concluded that bamboos appear to be suitable for use in constructed wetlands, though the treatment efficiency remained in question.

Further investigation was conducted within the scope of the research project "Bamboo for Europe" supported by the European Commission. Its main objective was to define and to overcome major problems and limitations to large-scale introduction of bamboo in the European Community. One option among them was to utilize two bamboo species in a constructed wetland and to compare their treatment efficiency with a standard wetland species (*Phragmites australis*). Two bamboo species (*Phyllostachis nidularia* and *Phyllostachis heteroclada*) were planted in VSFCWs treating primary effluent from septic tank or imhoff tank. The system, constructed in Portugal, was in operation and complied fully with the regulation imposed by European standard. The study concluded that there existed a high potential for further developments in Europe as well as in other areas. It also suggested that bamboo stands could be irrigated with secondary treated effluents so that surface water contamination could be avoided and biomass yields could also be utilized for several purposes as stated previously (De Vos 2000, De Vos 2004). Hence, bamboo can also be considered among the alternative plants to be applicable with SFCWs.

5.2 Presences of earthworms within the VSFCWs in Germany

The weather condition during the first sampling period on 13.06.2006 was very warm and sunny, with a temperature reaching 31°C. Earthworms were found by both methods. By manual digging, one earthworm was found at the depth of 10 cm. The extraction method was allowed to last for 10 minutes and the earthworm also appeared on the surface even after 5 minutes. In this case, it could be stated that earthworms can thrive in the VSFCWs, even on days when the climate is unusually warm in Germany. This is probably due to the fact that the habitat provided by the reed and gravel mitigates this dry and hot problem, whereas intermittent feed provides an aerobic condition and a food for the earthworms.

Nevertheless, the number of earthworms found in this study might have only been at the minimum range due to the sun and extremely warm weather stated previously. In reality it should be higher as the recommended sampling period in Germany is in autumn, because temperature effect of the earlier and later dates might lead to inactivity of the earthworms (Quack et al. 2003). The site and one of the earthworms found can be seen in the figure 5.2.

Figure 5.2: (left) Photo of the VSFCW in Flintenbreite settlement, and (right) Photo showing one of the earthworms found by this observation

To further confirm this hypothesis, more samplings were made at different seasons. Each trial was described below;

Date of sampling: 13.11.2006.

Outdoor temperature: 5 °C

Weather condition: rain shower

6 individuals of earthworm with similar red color but different size, suggesting all were from the same species, were extracted by the use of mustard powder extraction method. The size varied from the small ones with 4 cm up to the longest one with 10

cm length. From the field observation, they did not respond in a lively manner to the mustard powder solution as they did during the previous sampling in summer, which could imply that the worms at this period were already in the “stable” phase during the end of autumn (Edwards, 2004). Nevertheless, this result confirmed the prior investigation under the extreme weather condition during the summer time of the same year.

Date of sampling:	27.04.2007
Outdoor temperature:	24 °C
Weather condition:	sunny and warm

No earthworm was found on the date, probably due to the reason that the reeds were cut 2 weeks in prior to conducting this sampling, and consequently there was no cover for earthworms within VSFCWs. Moreover, there was no rain at all during the week. Incorporated with the warm and sunny period, the earthworm, if present, should tend to stay deep below ground. Therefore, they might reside within the wetlands, though not move upward after being applied with mustard pastes.

The last sampling was carried out in order to determine the distribution of earthworms over the VSFCWs. Also a hypothesis was made that earthworms might also reside in the soil outside the perimeter of VSFCWs. As a result, several sets of samplings were made on several areas both outside and within the VSFCWs.

Date of sampling:	13.07.2007
Outdoor temperature:	18 °C
Weather condition:	cloudy and rain shower

In this sampling, 3 sets were conducted. The first one resulted in 3 individuals of earthworms being extracted from the VSFCWs. The second, performed at 2 m distance from the VSFCWs site, resulted in zero number of earthworms. For the third set, it was undertaken at the area which constituted a lower density of plants. Two earthworms were found for this set.

Summarizing all those investigations, it could lead to the conclusion that earthworms are among the biological communities inside the VSFCWs, in addition to their presence within the HSFCWs in Australia (Davison et al. 2005). As a result, their integration into the SFCWs as a further enhancement could be possible. They could thrive during warm and sunny as well as winter period. Also, the effect from plant cutting could lead to the earthworms staying deeper below ground and the investigation could not be successfully made by the extraction method.

5.3 Experiment in Germany with raw wastewater

The experiment was firstly conducted in a small-scale study under a controlled condition. After some results were obtained, scale-up of the experiment was undertaken and the pilot-scale study was designed and implemented.

5.3.1 Lab-scale experiments

The average value of the analytical results from each mesocosm is presented in table 5.5.

Table 5.5: Average performance data from the experiment with raw wastewater at each HLR (cm/d) (in mg/L, except for pH)

Parameter	Influent	Effluent without worms HLR: 8	Effluent without worms HLR: 12	Effluent with worms HLR: 8	Effluent with worms HLR: 12
Mesocosm number		*1*	*2*	*3*	*4*
BOD_5	398.33	294.33	307	326	338
TOC	197.25	160.75	154	162.25	183
TN	75.45	63.83	65.25	72.38	80.60
NO_3	0.76	1.22	0.71	1.46	1.11
NH_4	56.38	49.12	51.45	56.80	60.28
TP	7.09	5.43	5.44	6.31	7.04
SS	187.25	178.50	204.25	189.5	176.25
pH	7.18	7.46	7.41	7.50	7.40

Considering the treatment performance from table 5.5, few removal processes occurred in every microcosm with respect to most of the parameters. This could be attributed to the large gravel sizes and little development in biological community within the microcosms, so that the effective detention time was too low. In terms of the solid reduction, the set with earthworms receiving HLR of 12 cm/d exhibited better performance than the one without. This was not the case for the set with 8 cm/d HLR where the microcosm without earthworms performed better. It might be because some of the earthworms cast was incidentally flushed out of the microcosm and was presented in the effluent due to the large size of gravel.

In terms of nitrogen value, higher NH_4 content was observed in the microcosms with higher HLR. In contrast, the microcosms with higher HLR exhibited lower NO_3 content. This could be because generally, higher feeding rate should allow lower amount of atmospheric oxygen, which is responsible for maintaining an aerobic condition in VSFCWs, into the microcosms. Hence, this leaded to lower nitrification rate. In any cases, the pH rose slightly though their values were still within the optimum condition for breeding earthworms.

From the table, a higher loading rate resulted in lower treatment performance. Nevertheless, even though the loading rate increased by 50%, the treatment efficiency was not directly proportionate. There was only a slight difference in terms of removal efficiency. For instance, the BOD removal efficiency from the microcosms without earthworms was 4% higher in the one with HLR of 8 cm/d than the one with HLR of 12 cm/d. For the microcosms with earthworms, the differences between both HLR were 3.5% in favor to the one with lower HLR. Therefore, in cases there was no threat or sign of clogging within the VSFCWs, one could possibly increase the HLR.

In the end, the survival rate of earthworms based on the mass was found to be 52% for mesocosm number 3 (2.75 g) and 53% for number 4 (2.65 g). This might be due to the fact that too few foods are available for them, as one study concerning the vermicomposting of dry sludge predicted that 200 mg was consumed by 1 g of earthworms per day (Prince et al. 1981). In this case, 5 g of earthworms were put into the mesocosms, their numbers underwent self-adjustment, and reflected this final earthworm biomass.

In terms of clogging, it was found that no clogging appeared in any of the mesocosms. Therefore, the impact of earthworms in terms of clogging reduction could not be studied. Further scale-up to the pilot-scale experiment was conducted with finer size of gravel in order to investigate this issue as well as to improve the treatment performance.

5.3.2 Pilot-scale experiments

First trial

The first trial was conducted during the second half of the year 2007. The average value of the analytical results from each VSFCW is presented in table 5.6.

Table 5.6: Average results from the 1st trial of the pilot-scale VSFCWs (in mg/L, unless stated otherwise)

Parameter	P0	P1	P2	P3
Planted		*Yes*	*Yes*	*No*
With earthworms		*Yes*	*No*	*Yes*
Temperature (˚C)	22.15	21.86	21.85	21.68
Conductivity (µS/cm)	1168	1096.55	1082.45	1138.89
pH	7.36	7.55	7.55	7.77
BOD	223.27	33.09	41	58
TOC	139.62	39.75	44.27	54.99
TN	77.82	64.92	57.9	66.48
NH_4	51.73	14.99	15.95	26.61
NO_3	2.29	37.53	28.62	27.05
NO_2	0.1	2.26	2	3.74
TKN	75.43	25.13	27.28	35.68
TP	8.47	6.62	6.70	6.62
SS	129.64	45.27	36.64	76.44

According to the table, pH, nitrate, and nitrite were the 3 parameters which demonstrated an increase in value from the effluent of all VSFCWs. These corresponded well with the results from the lab-scale experiment. The pH from both the influent and effluent fell within the optimal operating condition range and hence this should not be considered as an obstacle for the survivability of earthworms (Edwards 2004).

The raw wastewater contained very low nitrate and nitrite, which corresponded well with the general characteristic of untreated domestic wastewater. Comparing among each mesocosm, the effluent from P1 contained highest concentration of nitrate, whereas P2 and P3 exhibited similar level of nitrate in the effluent. Its values were increased by 19 fold in the case of P1, and approximately 14 fold in the case of P2 and P3. For nitrite, the increase was highest in the effluent from P3. Rising concentration of both values was due to nitrification process that occurred within the VSFCWs, in which there was the oxygen input by intermittent feeding of wastewater. Nitrate value in the final effluent from the planted unit with earthworms was 25% higher than the planted one without earthworms as well as the unplanted containing earthworms. Nonetheless, applying earthworms alone, i.e. without plantation, could at least achieve as high nitrification level as VSFCWs without any addition of earthworms. As nitrate and nitrite were generated, the total nitrogen removal could not achieve from VSFCWs as shown by the results. It could be stated that plants and earthworms contributed positively to the nitrification efficiency, probably due to symbiotic relationship between the microorganisms at the root zone of the plants and earthworms (Loehr et al. 1988). In order to achieve total nitrogen removal, a treatment system capable of denitrification process would be required.

After passing through the system, the effluent from all VSFCWs had slightly lower temperature comparing to the influent, nevertheless the water temperature was still within the optimum operating condition for an effective use of *Eisenia fetida* to treat solid wastes (Edwards 2004). Nevertheless, it should be noted that the study was conducted indoors. Therefore further study with respect to the real outdoor temperature condition should be conducted as the temperature could be a limiting factor especially during the winter period in temperate regions.

The systems were capable of removing BOD to some extent, in which the P1, P2, and P3 were capable of reducing BOD to 33, 41, and 58 mg/L respectively. Nevertheless, in order to comply with the German Water Recycling guideline, the BOD needed to be further removed, for instance by the 2nd-stage SFCWs, to achieve the BOD concentration lower than 20 mg/L in the effluent. This was also the case with the removal of SS, in which another treatment stage would be needed so that the value of

30 mg/L could be achieved with respect to the similar guideline. Further information regarding the German Water Recycling guideline could be found in appendix A.

Concerning both BOD and SS value, the effluent from P1 and P2 was qualitatively equal to the secondary effluent, whereas the effluent from P3 still contained too high concentration of both parameters (USEPA 2004). Therefore, it can be stated that the system with earthworms alone, i.e. the one performing as a filtration unit with earthworms, cannot achieve as high removal of organic and solids as P1 and P2. Due to the fact that the VSFCWs in this study were used as a primary treatment unit, i.e. without any pre-treatment, the system can be deemed very effective in removing BOD and SS to achieve the quality equaling those of secondary effluent. It should also be noted that the system utilizing both plantation and earthworms exhibited higher BOD removal whereas the system with only plantation showed higher SS removal.

The influent contained a low concentration of total phosphorus and the VSFCWs could not remove the phosphorus efficiently. This was not surprising as generally the removal of phosphorus within SFCWs were not considered effective as described in the previous chapter. To enhance the removal of phosphorus within the SFCWs, it is generally required to replace the substrates from gravel or sand to ones with high phosphorus adsorption capacities. In this case, applying earthworms into constructed wetlands might not enhance phosphorus removal. Nevertheless, the influent concentration could be considered too low to draw out a concrete conclusion.

In terms of the removal efficiency for the parameters that exhibit a decrease in value, the results are compared and shown in figure 5.3.

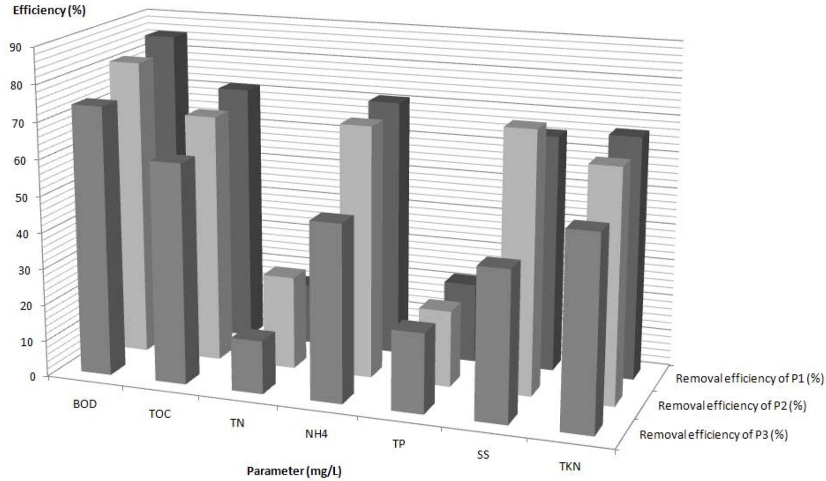

Figure 5.3: Removal efficiency of the 1st trial for each VSFCW according to each parameter

According to the figure, the BOD was efficiently removed by the unit planted with reed and earthworms, achieving an efficiency of more than 85%. This was closely followed by the planted mesocosm without earthworms (80%). The unplanted unit with earthworms exhibited the lowest BOD removal efficiency of approximately 70%. This trend was also applicable for the TOC removal efficiency. Hence, it can be stated that earthworms in combination with plantation within the VSFCWs positively contributed to the organic removal efficiency of the system. Moreover, normal VSFCWs might be more efficient in removing organic matter than the filtration-like mesocosm with earthworms.

In terms of the nitrogen removal efficiency, the TKN was removed by approximately 60% in P1 and P2, which corresponded with the average removal efficiency of 60% achieved by the 1st-stage French system VSFCWs in France (Molle et al. 2005). The comparability in this case could be due to the design of VSFCWs in this study that was based on the French system and the influent was also raw wastewater. Nonetheless, P3 could only achieve approximately 50% TKN removal efficiency. The explanation behind the 10% lower efficiency could be due to the plantation. Although direct nitrogen uptake by plants was only considered minor as stated in the prior chapter, the increase in microbial activities based on the root and rhizome could lead to higher efficiency. In this regard, earthworms together with plantation could also enhance the process as the TKN removal in P1 was higher than P2 by approximately 3%.

As already stated, the phosphorus removal from the system was minor and its efficiency was approximately 20%. No significant difference among each VSFCW was noticed. Hence, it could be stated that both plants and earthworms, whether applied altogether or separately put into the system, could not enhance the removal of phosphorus.

In order to conclude the discussion, it was clear that the efficiency was lowest for the unplanted unit with earthworms. Hence, its use was not encouraged and in order to treat raw domestic wastewater it was rather recommended to have a plantation as well as an integration of earthworms.

Second trial

During the first half of the year 2008, the 2^{nd} trial was undertaken in order to confirm the results analyzed during the 1^{st} trial. Average results from each VSFCW are demonstrated in table 5.7.

Table 5.7: Average results from the 2^{nd} trial of the pilot-scale VSFCWs (in mg/L, unless stated otherwise)

Parameter	P0	P1	P2	P3
BOD	217.83	33.50	45.17	68.33
TOC	150.72	37.82	40.20	53.62
COD	464.00	93.48	106.20	171.23
TN	120.70	103.53	101.42	105.05
NH_4	102.47	32.65	37.36	47.16
NO_3	1.99	65.25	58.77	46.63
NO_2	0.05	0.79	0.85	1.80
TKN	118.61	37.54	41.73	56.60
SS	139.6	40	25.8	45.20

It can be seen from the table that COD was analyzed during this trial. Its removal trend corresponded well with the elimination of BOD, in which the VSFCW with earthworms exhibited the best efficiency, followed by the VSFCW without earthworm and the unplanted unit with earthworms respectively. In terms of percentage, the COD removal efficiency was lower than 80% for every unit. Both P1 and P2 exhibited comparable efficiency to the similarly-designed French system achieving an average 79% COD removal obtained from the 1st stage VSFCWs (Molle et al. 2005). Lowest removal occurred with P3 and its effluent concentration could not comply with the 150 mg/L COD specified by the German effluent standard for a small domestic wastewater treatment system. This confirmed the remark pointed out from the discussion concerning the results from the 1st trial that it might not be encouraging to eliminate the use of plantation and to apply only earthworms for the treatment of domestic wastewater.

The removal efficiency including the COD parameter is also depicted in a similar illustration to the 1st trial in figure 5.4.

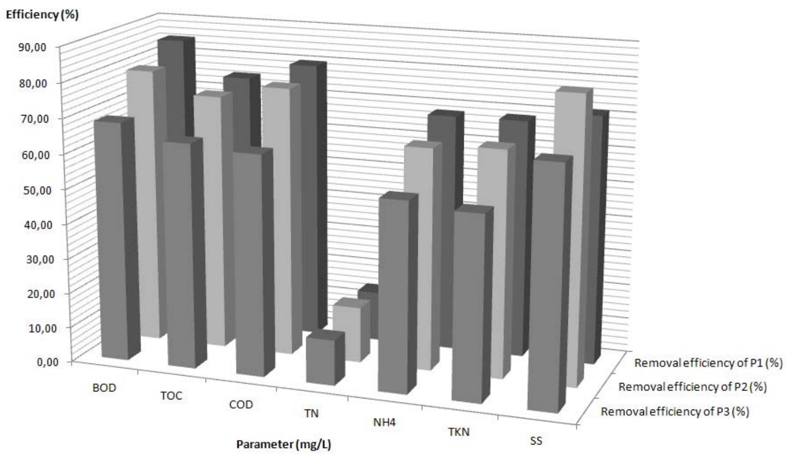

Figure 5.4: Removal efficiency of the 2nd trial for each VSFCW according to each parameter

The detailed discussions concerning the results obtained from the pilot-scale study were already explored in the previous section illustrating the results from the 1st trial.

Hence, the results obtained from the 2nd trial were to be discussed mainly based on the comparison between the two trials.

Comparison among each trial

To facilitate the comparison, the removal efficiency between both trials is shown side-by-side in table 5.8. Due to low phosphorus removal shown in the 1st trial, its analysis was omitted and the comparison could not be made. Further, no comparative discussion could be made concerning COD treatment because the analysis was only conducted during the 2nd trial.

Table 5.8: Comparison of the treatment efficiency between the two trials (%), NA: not available

Value	P1		P2		P3		Correlation
	1st trial	2nd trial	1st trial	2nd trial	1st trial	2nd trial	of trend*
BOD	85.18	84.62	81.64	79.27	74.02	68.63	Yes
TOC	71.53	74.91	68.29	73.33	60.61	64.43	Yes
COD	NA	79.85	NA	77.11	NA	63.10	NA
TN	16.58	14.22	25,60	15.98	14.57	12.97	Yes
NH_4	71.02	68.14	69.17	63.54	48,55	53.98	Yes
TKN	66.68	68.35	63.83	64.82	52.7	52.28	Yes
TP	21.86	NA	20,93	NA	21,86	NA	NA
SS	71.16	71.35	74.35	81.52	54.25	67.62	Yes

*This presented the consistency of the trend among each trial. For example, both trials showed a similar trend in terms of BOD removal efficiency, which was highest in P1, followed by P2 and P3 respectively.

According to the table, most of the parameter exhibited a similar correlation excepting the COD and TP which were analyzed only in one trial. Averaging the treatment efficiency from both trials, the P1 was capable of reducing BOD for approximately 85%, whereas the reduction was 80% and 71% for P2 and P3 respectively. For SS reduction, P1, P2, and P3 could achieve 71%, 78%, and 61% efficiency respectively.

The difference in terms of treatment efficiency between the two trials was in most cases minor. It ranged from as slight as less than 1% in several cases such as the SS reduction in P1 to as much as around 5% for the removal of BOD from P3 and the removal of NH_4 in P2. The exception was the removal efficiency of TN from P2 as well as SS from both P2 and P3, in which the margin was higher. The SS removal efficiency from P3 represented the biggest difference among the two trials with the value of around 13%. Hence, for the system acting as a vermi-filtration unit, there might be an inconsistent removal of suspended solids. In this case, further modification of the substrates might be required. Overall, it can also be noticed from table 5.8 that P1 showed the smallest difference whereas P3 showed the highest difference. For instance, the margin of BOD removal efficiency for P1 was less than 1%, however it was approximately 5% for P3.

Apart from the comparison of the removal efficiency between the two trials, the increase of NO_3 and NO_2 that was caused by nitrification due to an aerobic condition within the VSFCWs represented a similar trend for the nitrate. The effluent from P1 contained the highest concentration of nitrate, followed by P2, and P3 respectively. Nevertheless, the nitrite concentration was increased in a different pattern. Except the effluent from P3 which contained the highest nitrite concentration from both trials, the nitrite concentration was second highest in P1 followed by P2 from the 1st trial, and the opposite was shown from the 2nd trial. Nevertheless, the difference was only subtle, ranging from 0.06 to 0.26 mg/L in the 2nd trial and the 1st trial respectively. It can be stated that P3 exhibited the lowest effectiveness in terms of nitrification as the nitrate concentration was increased the least. Meanwhile, nitrite increased the most. Stated alternatively, plants altogether with earthworms revealed the highest effectiveness with consistency whereas applying earthworms alone exhibited the lowest nitrification efficiency. In cases where there was a need to completely remove nitrogen, another stage of treatment would be required to ensure denitrification. This could be in the form of the 2nd-stage HSFCWs, anaerobic pond, and so on.

Comparing the efficiency between both trials, one could perceive the correlation in all parameters apart from a slight difference in terms of nitrite generation. Hence, it can be stated that the results and the trend among each configuration of the VSFCWs were consistent. As each trial lasted for half a year, the results can basically be used as background information for any further detailed researches corresponding to this system. For simplification, the removal efficiency including nitrification efficiency (the increase of nitrate concentration in the effluent) among each configuration was ranked and summarized in table 5.9.

Table 5.9: Ranking of the efficiency based on the results from both trials

Parameter	P1	P2	P3
BOD	Best	2^{nd}	Worst
TOC	Best	2^{nd}	Worst
COD	Best	2^{nd}	Worst
Nitrification	Best	2^{nd}	Worst
NH_4	Best	2^{nd}	Worst
TKN	Best	2^{nd}	Worst
SS	2^{nd}	Best	Worst

It could be seen from this simplification table that the P1 (configuration with both plantation and earthworms) performed in most cases better than the rest. Only SS was an exception, in which the P2 (configuration with plantation though without earthworm) represented the best efficiency. In any cases, the worst performance came from the P3 (configuration without plantation though with earthworms), suggesting that plants also played a role within the treatment system. The plants would be of more importance than the earthworms as P2 achieved better treatment efficiency than P3. Nevertheless, combining both elements together would still be the best solution for VSFCWs according to the results from both trials. Hence, it is strongly suggested based on the results to integrate earthworms into any VSFCWs.

In terms of clogging, both trials showed no sign of clogging in any VSFCWs and there was no sludge produced over the surface of each mesocosm. This, incorporated with the 55% to 80% removal of SS, implies that the gravel size can be even finer if the source of the influent was from raw domestic wastewater. The removal of SS can be higher in compensation with some of the sludge formation that can occur over the surface of VSFCWs.

Focusing on the German Water Recycling guideline, the chart combining the effluent concentration from both trials was developed and shown in figure 5.5. This guideline can be seen in appendix A.

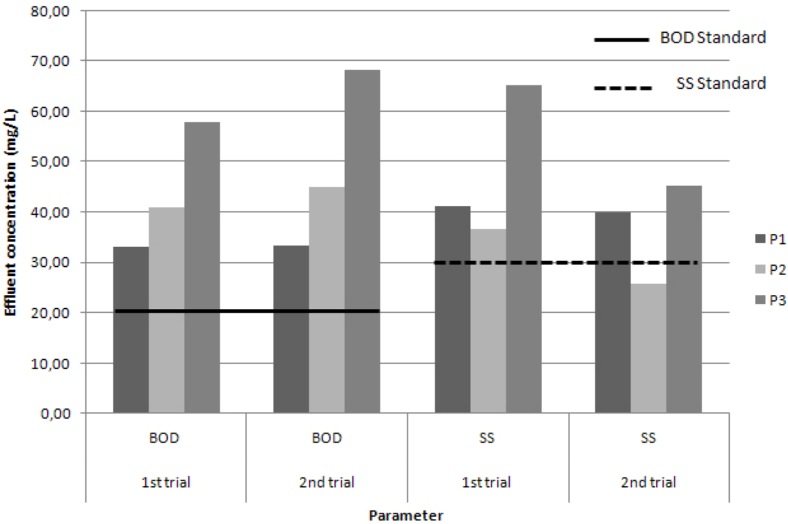

Figure 5.5: Effluent concentration in comparison with the German Water Recycling guideline

As discussed previously under the results and discussion of the 1st trial, another stage of treatment unit or enhancement of the VSFCWs is required in order to be applicable for recycling of the effluent in Germany. Figure 5.5 also reveals that only one effluent from P2 during the 2nd trial is in compliance with the guideline, although the effluent concentration is exceeded after averaging the SS concentration of P2 from both trials, i.e. 31.22 mg/L. It is clearly seen from this figure that the effluent after P3 poses the highest challenge in order to achieve the guideline as the concentration was highest compared with other two units.

Nevertheless, only the effluent from P1 complied with the German effluent standard for the small wastewater treatment system including the BOD lower than 40 mg/L and the COD of lower than 150 mg/L. The effluent from P2 still required a minor enhancement to further reduce its BOD concentration. In order to apply a 1-stage VSFCWs system to treat domestic wastewater as an on-site system, only by combining earthworms and constructed wetlands together could manage to meet the standard. As a result, it was encouraged to apply earthworms into the VSFCWs as well as to lower the size of the substrates for treating raw domestic wastewater, so that the efficiency could be enhanced.

5.4 Experiment in Thailand with swine wastewater

In this study, the preliminary experiment was established due to a concern over the strength of swine wastewater with respect to raw domestic wastewater. The results were used as baseline data for the scale-up of the experiment. As the strength of swine wastewater was considered very high, it was neccessary to design more than one stage of treatment unit. The lab-scale experiment was conducted with various configurations with respect to the use of 2-stages SFCWs in order to find the best design and operating condition for the pilot-scale experiment located on-site of the swine farm.

5.4.1 Preliminary experiment

For the preliminary experiment in Thailand, the ambient temperature during the study was around 26 °C at night and 28 °C during day time. According to the observation, the inflow through the reactors without earthworms was notably slower on day 5, especially in the reactor receiving swine wastewater with dilution factor of 1:1 and 1:2. In terms of the swine wastewater quality, only analytical results at the end of the trial are presented here due to the inconsistency from the results at the beginning of the run. This was due to the fact that the microbial communities might not yet fully developed in the biosystem. The average value from the experiment is shown in table 5.10. There was some reduction of organic matter in the experiment, which was reflected in approximately more than 50% of COD reduction for 1:1 dilution and 30% for the dilution factor 1:2. Low level of treatment was seen from the dilution 1:4.

Table 5.10: Average value from the experiment with swine wastewater (in mg/L, except pH)

Value	Dilution 1:1			Dilution 1:2			Dilution 1:4		
	Inf.	**Eff. 1**	**Eff. 2**	**Inf.**	**Eff. 1**	**Eff. 2**	**Inf.**	**Eff. 1**	**Eff. 2**
COD	1308	692.3	692.3	846.1	500	615.4	576.9	538.4	538.4
TS	29300	19500	21400	19200	17800	18700	15700	10900	13700
TDS	6700	2000	3200	5500	2500	3700	2100	300	900
NO_3	5.5	2.9	3.7	4.1	1.77	2.4	2.1	0.88	1.9
NH_4	4	1.3	2.6	1.8	1.3	2.3	1.6	0.2	1.3
pH	7.13	7.1	7.1	6.84	7.05	7.03	6.82	6.87	6.58

*Inf.: Influent; Eff. 1: Effluent from microcosm with earthworms; Eff. 2: Effluent from microcosm without earthworm

According to table 5.10, only the microcosm with earthworms receiving swine wastewater at a dilution 1:2 exhibited better performance than the one without them, whereas the efficiency was similar in the other cases. In terms of nitrate and ammonia-nitrogen reduction, it was clearly seen that the influent values of both parameters were very low. Nonetheless, focusing on the effluent quality there was a consistent trend that the microcosms with earthworms showed a better efficiency in reducing nitrogen. All solids were partly decreased in every microcosm. The ones with earthworms exhibited better solid reduction comparing to the units without earthworms for each set of dilution, ranging from 6% better efficiency in the non-diluted samples to 18% in the dilution 1:4. This was also in compliance with the results from the lab-scale experiment in Germany for the set receiving HLR of 12 cm/d.

In general, low treatment performance from this experiment can probably be attributed to several reasons. First, the height of the reactor was very short. Moreover, there was no inoculation phase to let the microbial communities within the cells became fully developed, including the missing of plantation. Lastly, the gravel size used in this experiment was larger than the size normally applied in constructed wetlands due to limitation in the capability of sieving equipment. Nevertheless, this study was conducted based primarily on the issues concerning clogging and the survivability of earthworms. The treatment performance was expected to improve after the scale-up to a larger-scale experiment.

Data concerning the survival rate of earthworms, including those from the lab-scale experiment in Germany, are shown in table 5.11. It was demonstrated that earthworms could thrive within the bed receiving swine wastewater, exhibiting the survival rate higher than 85%. Focusing on the study with domestic wastewater, the survival rate of earthworms based on the mass was found to be 52% for microcosm 3 (2.75 g) and 53% for microcosm 4 (2.65 g). Therefore, they should be able to tolerate the high strength of swine wastewater by residing within the gravel bed.

Table 5.11: The number of earthworms survived in each configuration including the value taken from the lab-scale experiment in Germany

Type of wastewater	Dilution factor	HLR (cm/d)	Number of alive earthworms before the experiment	Number of alive earthworms after the experiment
Swine	1:1	8	20	17
Swine	1:2	8	20	19
Swine	1:4	8	20	18
Domestic	1:1	8	11	5
Domestic	1:1	12	11	4

The results suggested that the organic within the wastewater provided them a very good source of food, which complied with the statement from other study stating that earthworms can consume organic waste and grow (Edwards 2004). The reason behind a 50% survival rate shown from the experiment with domestic wastewater could be due to the number of earthworms put in the microcosms, which is far greater than the quantity of food available. This resulted in a competition for food among them.

One related study concerning the vermicomposting of dry sludge predicted that 200 mg of organic was consumed by 1 g of earthworms per day (Prince et al. 1981). Therefore, the number of earthworms within the microcosms was undergone self-adjustment, and reflected to this final earthworm biomass. This reason also explained why the survival rate of earthworms in swine wastewater is higher than in domestic wastewater. Comparing that study to this experiment, the average BOD value of 400 mg/L implied that 1 g of earthworms could consume approximately 150 mg of organic, which is apparently lower than the wastewater sludge vermicomposting. It can also be seen that, for higher HLR, each individual of earthworms gained more weight despite of the decrease in number.

Without the presence of earthworms, there was some clogging in the reactors receiving high-strength swine wastewater, whereas this was not the case in the microcosms with earthworms. For the one in Germany with domestic wastewater, every microcosm showed no sign of clogging. As a result, it could be implied that earthworms could consume organic matter within the wetland body and this resulted in the non-clogged circumstance for the microcosms with earthworms.

In summary, the results preliminarily indicated that earthworms could thrive in both types of wastewater and help in reducing clogging potential. They could live within the bed under the tropical ambient temperature of up to 28 °C. Applying maximal recommended value of HLR for domestic wastewater to the bed receiving swine wastewater could lead to clogging of the bed unless the wastewater was diluted or the earthworms were applied.

To further investigate the potential of this concept, scaling-up to the lab-scale study was implemented to confirm the results obtained from this experiment. Moreover, as it was apparent that the high concentration of swine wastewater required more than only one stage of treatment, the lab-scale experiment was configured with various types of the 2-stages constructed wetlands in order to investigate the suitable configuration for further study.

5.4.2 Lab-scale experiments

The average results for all parameters are presented in table 5.12. The concentration of each parameter ranged from an influent (L0), the effluent from the 1st stage units (i.e. the influent to the 2nd stage units, L1, L3, L5, L7), to the final effluent (L2, L4, L6, L8). Moreover, the percent decrease of each parameter from each stage is also presented in this table, such as 74% reduction of BOD from the influent (L0) to the effluent from the 1st stage VSFCWs without earthworms (L1).

Results from table 5.12 also illustrate that all units are capable of treating the wastewater satisfactorily. Focusing on the results from VSFCWs-HSFCWs with earthworms configuration (from L0 to L4), the BOD could be reduced from approximately 800 to 50 mg/L and the SS from 7100 to 30 mg/L. Whereas the 2-stages VSFCWs had considerably higher organic as well as solids content in the final effluent, in which more than 100 mg/L for BOD and approximately 100 mg/L for SS. By comparing the difference between the results between two configurations, the explanation could be due to less surface area and length of the second-stage VSFCWs (5.73 dm^2) than the 2^{nd}-stage HSFCWs (11.7 dm^2).

Table 5.12: Average results from the analyses at each sampling point (mg/L, unless stated otherwise)

Sampling point number	BOD	COD	TKN	TVSS	SS	TS
L0	823	10627	814	5305	7148	9356
L1	215	552	131	49	347	1732
L2	119	246	94	15	51	1227
L3	131	342	110	25	147	1552
L4	54	236	105	5	31	1207
Average reduction L0-L1 (%)	73.9	94.8	83.9	99.1	95.1	81.5
Average reduction L1-L2 (%)	44.7	55.4	28.1	68.9	85.2	29.2
Average reduction L0-L3 (%)	84.0	96.8	86.5	99.5	97.9	83.4
Average reduction L3-L4 (%)	58.8	30.9	3.9	80.8	78.8	22.3
L5	140	360	126	36	156	1800
L6	128	250	100	17	91	1669
L7	200	484	100	32	237	1700
L8	155	329	75	19	128	1684
Average reduction L0-L5 (%)	83.0	96.6	84.5	99.3	97.8	80.8
Average reduction L5-L6 (%)	8.6	30.6	20.6	52.8	41.7	7.3
Average reduction L0-L7 (%)	75.7	95.4	87.7	99.4	96.7	81.8
Average reduction L7-L8 (%)	22.5	32.0	25.0	40.6	46.0	0.9

Comparing the percent removal of each treatment stage, the 1^{st} stage treatment exhibited better removal efficiency with respect to every parameter (70%-99%) relative to the removal efficiency of the 2^{nd} stage reactors. For the 2^{nd} stage reactors, the removal was highly variable, i.e. from 8 % to 68% in terms of organic removal to as low as 1% to 80% in terms of solid removal. This could result from the fact that in the 2nd stage units, the organic carbon available for biodegradation was more refractory, and hence less biodegradable. It could also be stated that the role of the 2nd stage was mainly to polish the quality of the effluent. Also in comparison, the reactor with earthworms had a better tendency of treatment performance than the one without earthworms except for the total TKN removal.

With respect to the role of earthworms on the treatment efficiency of the lab-scale VSFCWs, it can be seen in table 5.12 that the units containing earthworms (L0-L3 and L0-L5) exhibit better BOD removal efficiency than the units without earthworms (L0-L1 and L0-L7). This could be because earthworms and aerobic microbes act symbiotically to accelerate and enhance the decomposition of organic matter (Loehr et al. 1988). Hence, higher BOD removal was observed while applying earthworms into the VSFCWs. This suggested that earthworms contributed to the wastewater remediation during the treatment process within the VSFCWs.

After the influent passed through the 1st stage unit, the majorities of suspended solids were removed by this system for approximately more than 95% in every reactor. The remainder of the TS was in the soluble form that normally could not be effectively removed by VSFCWs. This was observed in the final effluent (after L6 and L8) in that the difference between the TS concentration from both units was very marginal (1669 to 1684 mg/L).

In terms of the overall treatment efficiency, the results are shown in table 5.13. For instance, BOD removal efficiency ranged from 81% in 2-stages VSFCWs without earthworms to 93% in VSFCWs with earthworms followed by HSFCWs.

Table 5.13: Overall treatment efficiency for each configuration (%)

Configuration	BOD	COD	TKN	TVSS	SS	TS
VSFCWs-HSFCWs without earthworms	85.6	97.7	88.4	99.7	99.3	86.9
VSFCWs-HSFCWs with earthworms	93.4	97.8	87.1	99.9	99.6	87.1
VSFCWs-VSFCWs with earthworms	84.4	97.6	87.7	99.7	98.7	82.2
VSFCWs-VSFCWs without earthworms	81.2	96.9	90.8	99.6	98.2	82.0

According to the table, the VSFCWs system with earthworms followed by HSFCWs exhibited superior treatment efficiency in most of the parameters than other configurations. Both configurations achieved the COD removal of more than 95%, which were marginally higher than the treatment efficiency of 79-90% using 1-stage VSFCWs conducted in Thailand (Kantawanichkul et al. 1999). Corresponding explanation for a better efficiency in this study could be due to more stages of treatment units. It was also very efficient to remove BOD, which was 7% better than similar configuration without earthworms and 10% better than both of the configurations utilizing 2-stages VSFCWs.

Only TKN removal was an exception, in which the removal efficiency was less than the 2-stages VSFCWs system without earthworms by approximately 3%. This could be because the feeding pattern for this configuration created an aerobic condition in both stages, allowing a higher level of nitrification. It was worth remarking that the TKN removal by these 2-stages VSFCWs was as efficient as the French 2-stages VSFCWs system designed for treating raw domestic wastewater (Molle et al. 2005). In terms of solid reduction, every configuration provided satisfactory results, in which the TS removal was over 80% and the SS removal was over 98%. It should also be noted that the VSFCWs-HSFCWs configuration had better performance than the VSFCWs-VSFCWs configuration.

In summary, the treatment performance of the lab-scale reactors containing earthworms was in most cases better than the ones without earthworms. In terms of the configuration, the VSFCWs with earthworms sequentially followed by HSFCWs had generally the best treatment performance. Therefore, it is recommended that designs for further study scaling up from lab-scale constructed wetlands to pilot-scale constructed wetlands should be based on this configuration.

5.4.3 Pilot-scale experiments

In this study, the average results for six months are presented in table 5.14. The concentration of each parameter that can be seen in this table ranged from an influent (P0), the effluent from the 1st stage units (i.e. the influent to the 2nd stage units, P1 and W1), to the final effluent (P2 and W2). Also, standard deviations for every parameter are given in parentheses. The percentage removal of each parameter at each stage is also presented in this table, such as 95.4% reduction of BOD from the influent (P0) to the effluent from the VSFCWs unit without earthworms (P1).

Table 5.14: Results from the analyses at each sampling point (mg/L, unless stated in percentage)

Sampling point	BOD	COD	TKN	SS	TVSS	TS
P0	10060	47009	2212	44862	36618	50413
(SD)	*(7485)*	*(26253)*	*(1953)*	*(26183)*	*(21081)*	*(31468)*
P1	459	1411	125	141	74	2250
(SD)	*(618)*	*(1952)*	*(149)*	*(129)*	*(49)*	*(459)*
P2	136	338	95	39	20	1745
(SD)	*(173)*	*(313)*	*(126)*	*(39)*	*(19)*	*(362)*
W1	412	944	171	102	63	2314
(SD)	*(543)*	*(1140)*	*(129)*	*(66)*	*(39)*	*(692)*
W2	157	346	133	44	24	1551
(SD)	*(125)*	*(228)*	*(109)*	*(47)*	*(24)*	*(306)*
Average reduction P0-P1 (%)	95.4	97	94.4	99.7	99.8	95.6
Average reduction P1-P2 (%)	70.3	76	24.2	72.5	73.5	22.4
Average reduction P0-W1 (%)	95.9	98	92.3	99.8	99.8	95.4
Average reduction W1-W2 (%)	62	63.4	22.4	56.9	62.7	33

Firstly, it could be noted that influent concentration in this study was significantly higher than the one analyzed during the lab-scale experiment. This suggested that the decomposition had already occurred during the preparation and the transportation of wastewater from Nakornpathom province to Bangkok, which in general took 3-4 hours. For instance, taken directly at the swine farm, the BOD value was approximately 11 times higher. This was among the reasons one needed to scale-up the experiments to the real scale in order to confirm the results obtained from the lab-scale studies.

The results from table 5.14 show that both units were capable of satisfactory treatment of the wastewater. For instance, the results from the system with earthworms (from P0 to W2), the BOD could be reduced from approximately 10000 to 157 mg/L and the

SS from 44000 to 44 mg/L. Whereas the system without earthworms had slightly lower organic as well as solid content in the final effluent, which was 136 mg/L for BOD and approximately 39 mg/L for SS.

The VSFCWs in Thailand was configured with a finer size of gravel and sand as well as deeper layer of the substrate with the aim to enhance treatment efficiency as well as to significantly observe the effect of earthworms on clogging reduction, hence there was better removal at a tradeoff with higher sludge accumulated over the surface of the VSFCWs. In Germany, there was no sludge produced at all even after the study period was over, although the quantity of sludge produced in Thailand was apparent. Moreover, the study in Thailand was conducted outdoors, in which the temperature effect from tropical climate as well as the corresponding direct sunlight would be considered more apparent. The average outdoor temperature in Thailand was higher than 30˚C most of the time, which greatly enhanced microbial reaction. For example, an optimal temperature range for nitrification was from 25 to 35˚C (Cooper et al. 1996), which was achievable in Thailand though not in Germany.

Among each stage of treatment, the effluent after the 1st stage treatment (P0-P1 and P0-W1) exhibited better removal efficiency in every parameter than the removal efficiency of the final effluent from the 2nd stage units (P1-P2 and W1-W2). The removal was considerably lower, especially in terms of TKN and TS. For TKN, the reason was due to continuous feeding pattern of HSFCWs, which resulted in an anaerobic process within the system. Consequently, TKN could not be efficiently removed. The low TS removal was probably because most of the remaining solids were already in dissolved form after the 1st stage treatment. Hence, they could not be further removed by the wetlands' substrates. Apart from these two parameters, average reduction of organic content was in the range between 60 to 70%. This might be because the major part of carbon available for further biodegradation was already used up in the 1st stage units. Therefore, the 2nd stage treatment units were used mainly to further polish the effluent quality.

The results also revealed that the systems could not achieve the BOD obligation based on the Thai standard for the effluent from the swine farms, in which 60 and 100 mg/L are required for large-scale and medium-scale swine farms respectively. Nevertheless, the COD concentration in the final effluent from both systems was in compliance with the standard for the medium-scale swine farm, which required that it must not exceed 400 mg/L. In terms of SS, both units achieved satisfactory results in that they met the requirement for both scales of the swine farms only after passing through the 1st stage VSFCWs. Therefore, in order to comply with the BOD standard, another polishing unit would be needed so that the effluent would contain below 60 mg/L or 100 mg/L of BOD for large-scale and medium-scale farms respectively. The addition of polishing pond or even another SFCW are among the possibilities indicated. Illustration of the effluent concentration in comparison with the standard for each type of farm is shown in figure 5.6. As a supplement, the translation of the Thai standard for swine wastewater effluent can be seen in appendix B.

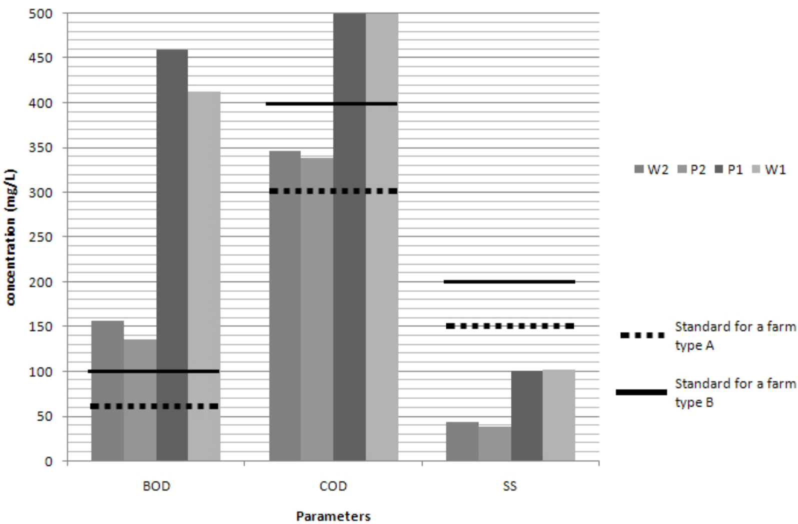

Figure 5.6: Effluent concentration in comparison with the Thai's effluent standard for swine wastewater effluent

According to the figure, a farm applicable of type A is required to have more than 600 Livestock Units (equivalent to higher than 5000 individuals of swine), whereas farms with swine ranging from 6 up to 600 Livestock Units are considered type B (equivalent to the number ranging from 50 to 5000 individuals). As larger farms tend to possess higher environmental risk, the standard for the type A farm is more stringent than for the type B farm. The results concerning overall treatment efficiency are shown in table 5.15.

Table 5.15: Overall treatment efficiency for each configuration (%)

Configuration	BOD	COD	TKN	SS	TVSS	TS
Removal efficiency of the system without earthworms (P); *(SD)*	98.65 *(1.35)*	99.28 *(1.6)*	95.72 *(11.71)*	99.91 *(2.04)*	99.95 *(1.25)*	96.54 *(11.17)*
Removal efficiency of the system with earthworm (W); *(SD)*	98.44 *(1.79)*	99.26 *(1.64)*	93.99 *(10.09)*	99.90 *(1.64)*	99.94 *(0.24)*	96.92 *(10.4)*
Difference of removal efficiency between the VSFCWs with and without earthworms (P1 to W1)	0.47	0.99	-2.10	0.09	0.03	-0.13

According to table 5.15, the system with earthworms exhibited comparable treatment efficiency in several parameters to the one without earthworms. Both achieved the BOD and COD removal of more than 98%, which were marginally higher than the treatment efficiency of 79-90% from other study with stand-alone VSFCWs conducted in Thailand (Kantawanichkul et al. 1999). Subsequent clarification for the improved removal efficiency in this study could be due to the increased number of stages of treatment units. Removal of solids was also very efficient. TKN removal was an exception. The removal efficiency of the unit with earthworms was less than the unit without earthworms by 1.7%. This corresponded well with a prior lab-scale study in Germany with domestic wastewater. However, the TKN removal of both configurations was as efficient as the 2-stage VSFCWs system developed in France that was designed for treating raw domestic wastewater, i.e. wastewater without any pre-treatment by septic tanks (Molle et al. 2005).

Focusing only on the effluent after the 1st stage unit, one could see that there was a minor difference between both units in terms of the removal efficiency. Nevertheless, upon completion of the study, the sludge produced on the surface of the VSFCWs showed remarkable variations in quantity. The height of sludge was measured at 15 cm for the unit with earthworms compared to 25 cm for the unit without earthworms. This implied that the sludge produced was 40% lower with the integration of earthworms. This could be attributed to the symbiotic relationship between earthworms and aerobic microorganism that accelerated and enhanced the decomposition process of the organic matter (Loehr et al. 1988). In the earthworm unit, the sludge volume for six months was calculated to be 100 L less than the volume in the unit without earthworms. This also meant that the frequency of sludge removal could be decreased in the case of the VSFCWs with earthworms, which could lead to lower operational costs. Clogging of the 1^{st} stage bed was also observed in the unit without earthworms where the influent from each feeding cycle took a longer time to infiltrate the bed. This could be due to large production of sludge. Nevertheless, there was no clogging at either of the 2^{nd} stage beds as most of the suspended solids were already removed at the 1st stage beds.

In terms of the organic loading rate with respect to BOD, the treated concentration can be seen in figure 5.7. A general trend between the increased BOD loading and the increased treated load up to the highest loading rate of approximately 1800 g/m2-d was apparent for both P1 and W1 units from this figure. The figure revealed a considerable variation in terms of the treated effluent at the lower BOD loading rates less than 250 g/m2-d. The effect of the background BOD, due to release from previously settled influent TSS and plant decomposition was especially evident in systems with low loading rates.

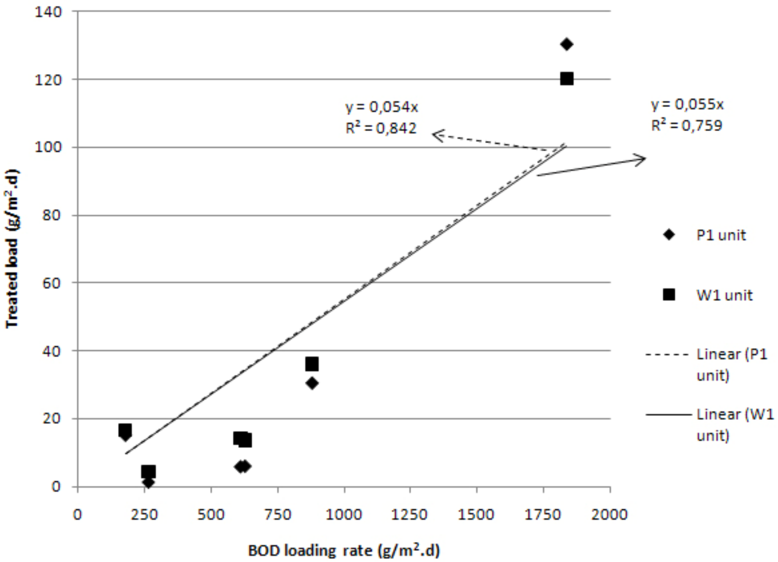

Figure 5.7: Treated BOD concentration with respect to the BOD loading rate

It could also be seen that there were only minor differences between the effluent from P1 and W1 units. At the high BOD loading rate, the P1 unit exhibited slightly better BOD removal performance than the W1 unit. However, for the BOD loading rate lower than 1000 g/m^2-d, the treated load was better in W1. Unfortunately no data point was available in the range between the BOD loading rate of 1000 to 1800 g/m^2-d to draw a firm conclusion of the BOD treatment efficiency between the two units. Moreover, the treated BOD load exhibited under the lower range of BOD loading rate corresponded well with the results from the pilot-scale experiment in Germany, in which the VSFCWs with earthworms performed better in terms of BOD removal. It was comparable because the operation in Germany used raw domestic wastewater as an influent. The BOD loading rate of such wastewater on average was equivalent to 26.47 g/m^2-d, which was considered on the low side regarding to the high concentration represented in swine wastewater.

A more conservative analysis of figure 5.7 indicated that the VSFCW without earthworms should not be loaded at a very high rate, i.e. 1750 g/m^2-d as the performance tended to decrease slightly in comparison to the VSFCW with earthworms. However, there is only one data point above 1000 g/m^2-d and it was at approximately 1800 g/m^2-d, which was almost two times higher. More analysis is needed in order to investigate the performance of both types of VSFCWs under extremely high loads.

Moreover, the COD removal rate with respect to its loading rate is shown in figure 5.8.

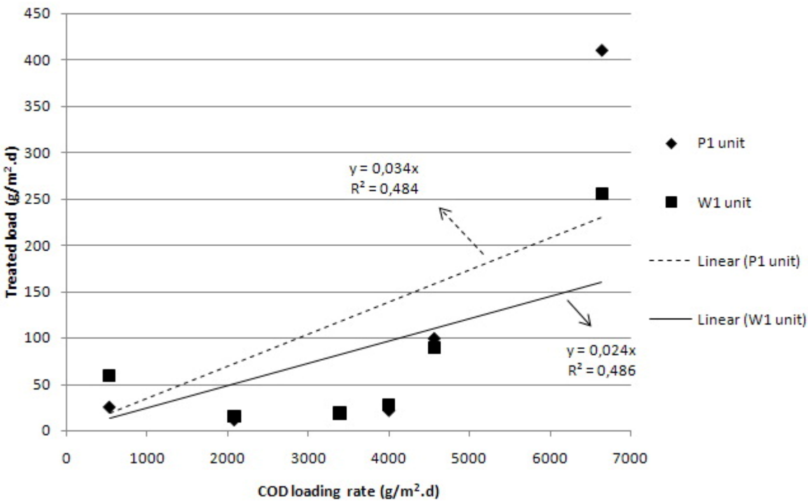

Figure 5.8: Treated COD concentration with respect to the COD loading rate

All COD loading rate applied into the VSFCWs during the study was significantly higher than the 20 g/m^2.d value specified in the German guideline for the VSFCWs to treat domestic wastewater (ATV-DVWK 2004). Nevertheless, the system could treat the COD efficiently unless the COD loading rate was higher than 4500 g/m^2-d. If this is the case, both P1 and W1 will perform at considerable lower effectiveness as shown in the COD loading rate of 6700 g/m^2-d. From the loading rate of 4500 g/m^2-d upward, the W1 unit exhibited better efficiency whereas the P1 unit achieved better efficiency for the rate below that value. It should be noted that there was only a minor difference in terms of the performance for the loading rate between 2000 to 4500 g/m^2-d.

At the extremely high rate, the VSFCW with earthworms could manage to treat the COD far more efficiently than the unit without earthworms. The difference was approximately 150 g/m^2.d, accounting for 37.5% less COD load in the effluent. Nevertheless, it was recommended that the COD loading rate should not exceed 4500 g/m^2-d as such high rate could result in the higher-than-norm treated load.

Apart from the BOD and the COD removal rate, SS removal rate with respect to SS loading rate is also illustrated in figure 5.9. Here, the SS removal was more variable than the BOD as depicted by the R^2 value calculated from the trend line shown in figure 5.10. Because of this reason, attempting to draw a concrete conclusion from the graph is complicated. At the loading higher than 4000 g/m^2-d SS, the treatment performance began to reverse. The higher SS loading rate would lead to better treatment. This might be due to extremely high solid content that could serve as another filter layer, which would lower the rate at which the influent passed through the system. As a result, the performance was increased due to longer detention time within the VSFCWs and enhanced sedimentation over their surfaces

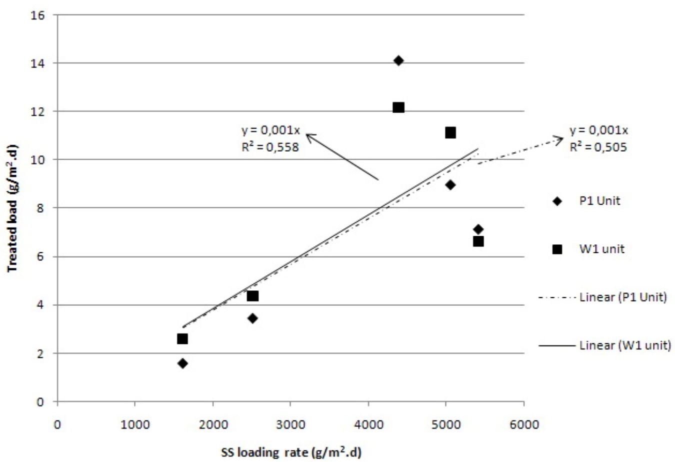

Figure 5.9: Treated SS for the influent with SS concentration more than 10000 mg/L with respect to the SS loading rate

Nevertheless, if the two SS loading rate values of 4300 and 5300 g/m^2-d were to be excluded, the trend line would reflect a definitive correlation. In such case it could be stated that the system without earthworms exhibited better SS removal than the one with earthworms. More research should be undertaken under extremely high loads of SS. But according to the results from this study, it was recommended not to apply the SS loading rate higher than 4000 g/m^2-d as an unforeseeable result might be observed from the treated load. Also, the correlations of both SS and BOD were comparable to the findings from another study observing the relationship between removal rates and loading rates of VSFCWs receiving high-strength wastewater, which had higher removal rates at higher loadings (Kantawanichkul et al. 2009).

For the biomass as well as dry matter of the plant materials, the results are shown in table 5.16.

Table 5.16: Results concerning the plant biomass and dry matter

	Wetlands surface area (m^2)	Plants biomass before drying (g/m^2)	Plants dry matter (g/m^2)
P1	1	4500	738
P2	1.26	7936	1341
W1	1	2500	539
W2	1.26	6746	1267

The system with earthworms exhibited considerably lower plants biomass than the one without. For the 1^{st} stage units, there was approximately 44% less biomass produced within the VSFCWs with earthworms. In contrast to a majority of studies examining earthworms as plant growth promoters, in which it was shown that 79% of the experiments conducted so far showed an increase in plant biomass and only 9% of the studies reported a decrease (Scheu 2003). This could be due to higher competition for food with earthworms resulting in lower growth of plants. Nevertheless, this point should be further studied. Concerning the biomass of the 2^{nd} stage units, the difference among the same stage was less significant than the 1^{st} stage units. However, in comparing these results with those from the 1^{st} stage units, a considerably higher biomass production was observed. There are two possible explanations. Because parts of the ammonia nitrogen within the wastewater were converted to nitrate after passing through the aerobic VSFCWs, they were more readily available for plants and hence more growth was observed. Moreover, plant growth in the 1st stage could be affected by ammonia toxicity due to high ammonia content in the influent.

There was no major difference in terms of the removal efficiency between the pilot-scale SFCWs with earthworms and the ones without earthworms. The plant biomass was higher for the SFCWs without earthworms. Although the latter exhibited slightly better overall treatment performance, sludge production over the surface of VSFCWs was considerably higher. This could imply that earthworms contributed positively in this aspect and their addition into the 1st stage VSFCWs would be recommended.

6 Conclusions and Recommendations

For the investigation concerning the choice of plants to be advantageously used in constructed wetlands, there are more than one "most appropriate plant species" in most regions. As a result, it might not be necessarily needed to always use the conventional plants in SFCWs. To perform the selection, the operators should weight the results from each criterion according to their preference, and determine which plant will be used in the system. The recommendation table presented in this thesis can serve as a valuable selection tool. To ensure that the resources will be recovered, significant efforts from every stakeholder are required as a part of good managerial measures. Several "how-to" practices and responsible stakeholders should be clearly specified and followed, for example who will decide how to utilize the plants after harvesting for each season, who will make use of them, and who will obtain the benefits from such practice.

It can be stated from the theoretical investigation that earthworms could be included in the VSFCWs as an enhancement to reduce clogging or even increase the treatment performance. The observation at the VSFCWs in Flintenbreite confirmed the presence of earthworms within the substrates, even under unfavorable climate condition such as during the warm summer period with strong sunlight or the winter period. It was also worth noting that earthworms might not be active during the period after the plants were just harvested as they could stay further belowground. This implies that they are performing a part among the bio-community and that it should be possible to scientifically integrate them into the constructed wetlands.

The experimental results from the lab-scale studies in Germany and Thailand indicated that earthworm could sustain both the raw domestic wastewater and swine wastewater as well as help reducing clogging in the case of swine wastewater treatment. The results also served as a valuable baseline data for further design of pilot-scale VSFCWs in Germany as well as the 2-stages SFCWs in Thailand.

For the pilot-scale study in Germany, applying earthworms altogether with plants in the VSFCWs could achieve higher BOD removal as well as higher level of nitrification by 25% than applying earthworms without plantation or using VSFCWs alone. The removal of SS was second to the planted VSFCW without an addition of earthworms, although the difference was considered minor. The treatment efficiency was comparable to that of the French system, even being under the higher load.

Still, the system needs another stage of treatment so that final effluent can be in compliance with the German BOD and SS guideline for water recycling of 20 and 30 mg/L respectively. If financial constraint poses a limit, the modification of the gravel size to be finer might also be an option. In this case, one should further explore its potential over the sludge accumulated over the surface of VSFCWs.

For the part in Thailand, the results revealed that the systems could not achieve the Thai BOD standard of 60 mg/L. Nevertheless, the COD concentration in the final effluent from both systems is in compliance with the standard for the medium-scale swine farm, which requires that it must not exceed 400 mg/L. In terms of SS, both units achieved satisfactory results that they met the requirement for both scales of the swine farms only after being treated by the 1^{st} stage VSFCWs. Therefore, in order to comply with the BOD standard, another polishing unit would be needed so that the effluent would contain below 60 mg/L or 100 mg/L of BOD for the large-scale and medium-scale farms respectively. The system including earthworms achieved significantly lower sludge that was accumulated over the surface of VSFCWs by 40%. This could be regarded as highly beneficial as there would be less concern with respect to the removal of sludge as well as its associated treatment afterward. The properties of sludge should be further studied and compared in order to investigate the potentials for further reuse.

In summary, applying earthworms into the constructed wetlands was strongly suggested as they had the potential to reduce the accumulated sludge within the VSFCWs under a strong load of high-strength wastewater. Also, this configuration was at least as efficient as using VSFCWs alone, which in some cases were slightly better such as the BOD removal efficiency of VSFCWs receiving raw domestic wastewater.

Still, the integration of earthworm into VSFCWs needs further optimization concerning its operation. For instance, the gravel layer can be finer if the source of the influent is domestic wastewater, whereas it should be instead coarser if the influent is swine wastewater. There is also the potential to increase the HLR higher than the recommended value into the wetlands treating raw domestic wastewater by using earthworms as an enhancement. In such a case, the area requirement can be lowered. Consequently, the gravel which predominantly share a major construction cost of the constructed wetlands is needed less. The results are less money required to build the system, which can make this system even more attractive. Further research might be needed in order to investigate the optimum operating condition of this integration, such as examining the optimum loading rate, the bacteriological study of the substrates, optimum earthworm density, and so on. Also, the effect that earthworms have on plant growth in association with the application of constructed wetlands should also be researched.

Incorporating the plant-related resource recovery aspect with the application of earthworm-assisted constructed wetlands, the whole approach can be integrated into the ecological sanitation concept especially for any new settlements or demonstration villages aimed toward closing the loop of wastewater. The constructed wetlands with the support from earthworms can play a major role for the treatment of greywater or even blackwater. Several corresponding components can be reused. The plants possessing high utilization options can be reused after being harvested in several ways based on the preference of stakeholders. Sludge accumulated over the surface of VSFCWs can be further vermicomposted and be used as a soil conditioner. If the treated effluent is complied with the standard, it can also be put back directly into the land for agricultural purpose.

As a concluding remark, the outcomes as well as outlook with respect to each objective previously outlined under the background chapter were concisely summarized below;

Investigating the potentials of adopting alternative plants which possess more utilization options based on each climatic region

- It was found that alternative plants could serve as the replacements to the conventional plants especially when the factors concerning utilization options and productivity were taken into account. Under each climatic region, there is more than one alternative plant that could be applied in constructed wetlands.

Investigating the probability of finding earthworms that might be presented as part of the biocommunity within the VSFCWs

- By finding earthworms within the VSFCWs under various seasons annually, it could be stated that they were already among the several organisms residing within the VSFCWs. Hence, the systematic integration of the earthworms species generally used to treat and mineralize solid wastes into the VSFCWs in order to help alleviating the clogging problem and probably to improve the treatment performance should be highly feasible.

Investigating the potentials of using earthworms in the lab- and pilot-scale constructed wetlands to treat raw domestic wastewater in Germany

- The VSFCW with earthworms exhibited better treatment performance than the VSFCW without earthworms in most parameters although their effects on the mitigation of clogging could not be concluded during this study due to no sludge occurring over the surface of VSFCWs. Based on the design of the VSFCWs, the HLR, already exceeding the guideline value in this research, can be further increased. The result would be the reduction of surface area required to build the treatment system utilizing constructed wetlands. Further research should aim to investigate the effect of increased HLR to the treatment performance as well as clogging or to observe the intrinsic difference in terms of the interaction between the VSFCWs with earthworms comparing to the normal VSFCWs.

Investigating the potentials of applying this concept in the lab- and pilot-scale constructed wetlands to treat swine wastewater in Thailand

- It could be stated that this technology was successfully designed and implemented in Thailand in order to treat swine wastewater from the swine farm in Thailand. The system could significantly reduce suspended solids, and consequently mitigate the clogging, without any significant difference in terms of the treatment performance comparing to the unit without earthworms. Further research should consider the topics surrounding sludge produced over the surface of VSFCWs, e.g. the difference in terms of properties between the sludge from the unit with earthworms and without, the treatment system that should be applied to treat it, and so on.

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8 Appendices

8.1 Appendix A: German Water Recycling guideline

Parameter	Unit	Value
pH		6-9
Turbidity	NTU	1-2
DO	% of saturation	80-120
BOD_5	ppm (mg/L)	20
TSS	ppm (mg/L)	30
Fecal coliforms	CFU/100 mL	100
Total coliforms	CFU/100 mL	500

8.2 Appendix B: Thai standard for the effluent from swine wastewater farms (translated from the Thai version)

The standard was set by the Thai Pollution Control department under the Ministry of Natural Resource and Environment.

Table 8.1: Standard for controlling the effluent from swine farms

Parameter	unit	Limit		Analyzing method
		Standard A	Standard B	
1. pH	-	5.5-9	5.5-9	pH meter type Electronmetric Titration
2. BOD	mg/L	60	100	Azide Modification หรือ Membrane Electrode
3. COD	mg/L	300	400	Potassium Dichromate Digestion type Open Reflux or Closed Reflux
4. SS	mg/L	150	200	Glass Fiber Filter Disc and oven-dried under 103 - 105 ˚C

Note:

1. Standard type A applies for controlling the final effluent from the swine farm type A and the standard type B applies for controlling the final effluent from the swine farm type B and C

2. Classification of the type of swine farm uses Livestock Unit as a measurement unit and can be described as follow;

2.1 Type of swine farm, which can be divided into 3 types
(1) Type A having Livestock Unit higher than 600 (equivalent to swine more than 5000 individuals)
(2) Type B having Livestock Unit from 60-600 (equivalent to swine from 500 to under 5000 individuals)
(3) Type C having Livestock Unit from 6 to 60 (equivalent to swine from 50 to under 500 individuals)

2.2Measure used to calculate Livestock Unit
When 1 Livestock Unit is equivalent to the total weight of 500 kg swine

by average weight of swine used for breeding purpose equal to 170 kg
average weight of growing swine equal to 60 kg
average weight of wean swine equal to 12 kg

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EDUCATION

Jul 05 – current Hamburg University of Technology (TUHH), Germany
Doctoral researcher at the Department of Wastewater Management and Water Protection
Topic: Feasibility of implementing earthworm-assisted constructed wetlands to treat wastewater

Oct 02 – Mar 05 Hamburg University of Technology, Germany
M.Sc. in Environmental Engineering (English Program)
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WORK EXPERIENCES

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- Promote and market Carbon Reduction label and Carbon Footprint program in Thailand
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- Responsible to market the voluntary emission trading system (V-ETS) in Thailand

Jan 04–Apr 04: Intern; **Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany**; Ecosan sectoral project

- Provided the knowledge support for the implementation of sustainable sanitation principles in several projects around the world
- Developed and published the technical datasheet concerning several components of ecological sanitation

May 01–Jun 01: Intern; **Nippon Koei Co. Ltd., Tokyo, Japan**; Overseas Consulting Administration (Water Resource and Energy Division)

- Reviewed the Water Resource Development Project in Thailand
- Investigated the flood control system along River Arakawa

Mar 01–Apr 01: Intern; **Consultants of Technology Co. Ltd., Bangkok, Thailand**; Environmental Studies Division

- Participated in the implementation of several Environmental Impact Assessment (EIA) projects
- Studied and proposed the feasibility of implementing ECO-Park (ecological industrial estate) concept for Thailand

PROJECT EXPERIENCES

2009 Researcher under the Research and Development Committee, the Senate, Thailand
Topic: Research on Thailand's environmental law

2009 Researcher under Chulalongkorn University
Topic: Using EM bacteria to treat slaughterhouse and cafeteria wastewater

2007-2008 Research assistant under the framework of Thailand Research Fund (TRF)
Topic: Earthworm-assisted Constructed Wetlands for Swine Wastewater Treatment

2003 Student project in Germany concerning Huber Prize competing with other graduate students from German's universities
Topic: Nature-orientated wastewater treatment technologies; awarded the second prize

SCIENTIFIC JOURNAL AND CONFERENCE PUBLICATIONS

Chiarawatchai N. and Otterpohl R. (2008). Options for improving the effectiveness nd potentials for a sustainable resource recovery in constructed wetlands. In: *Efficient Management of Wastewater*, Al Baz I., Otterpohl, R., and Wendland, C. (ed.), Springer-Verlag, pp. 163-175.

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Chiarawatchai N. and Otterpohl R. (2006). Potentials of earthworm-assisted constructed wetlands: principals and preliminary results. In: *Proceedings of the 10th IWA International Conference on Wetland Systems for Water Pollution Control, 23-29 September, Lisbon, Portugal,* pp. 1067–1075.

AWARDS:

2004 Second place for the Huber Technology prize 2003/2004 among the works submitted by graduate students throughout Germany

2002 H.M. King Bhumibol Gold Medal Award for achieving the highest major undergraduate GPA in Environmental Technology Program

MEMBERSHIP AND EXTRACURRICULAR ACTIVITIES:

Since 2007 Member of the German Association for Water, Wastewater and Waste (DWA)

2004 Participated as a promotion team leader of "Thailand Day 2004" at TUHH

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ADDITIONAL SKILLS

- Fluent in written and conversational Thai and English
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Ziel dieser Forschungsarbeit war die Untersuchung des Potentials zur Steigerung der Effizienz von Pflanzenkläranlagen durch Zugabe von Regenwürmern. In Deutschland zeigte sich für die mit Regenwürmern unterstützen Pflanzenkläranlagen eine deutlich bessere Abbauleistung als für das einfache Pflanzenkläranlagenverfahren. In Thailand war in Versuchen mit den Regenwürmern eine um 40 % geringere Schlammbildung zu beobachten. Zusätzlich wurden verschiedene Pflanzen mit hohem Potenzial zur Wertstoffrückgewinnung in Bezug auf die Anwendung in Pflanzenkläranlagen untersucht. Eine Empfehlungstabelle mit 13 Pflanzenarten wurde entwickelt. Für jedes der betrachteten klimatischen Gebiete eignen sich mehrere Spezies.

The aim of this research was to add the earthworms into the constructed wetlands, both in Germany and Thailand, in order to investigate whether they could improve the treatment performances. For Germany, earthworm-assisted constructed wetlands exhibited better treatment efficiency than conventional vertical subsurface-flow constructed wetlands and the unplanted constructed wetlands with earthworms. For Thailand, the production of sludge on the surface of wetlands was reduced by 40% with earthworms. Apart from that, alternative plants with high resource recovery potential were proposed. The recommendation table was developed with 13 suitable species. There are more than one “most appropriate species” in each climatic region.

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