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Potential for the adoption of vermicomposting to stabilize sewage sludge in Mexico

Viewpoints from the main actors

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Thesis for the fulfillment of the
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I would like to start by dedicating this thesis to my special ones.

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A mi padre, que aunque ya no puede estar aquí siempre está presente.

A Julián, por su inagotable paciencia, cariño y buenos consejos.

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Cristabel Meza

Lund, Sweden, May 2010

i

Abstract

The treatment of sewage sludge is often a neglected part of wastewater treatment operation in developing countries. It is generally perceived as an additional operational cost and its importance for an adequate sanitation system is not fully recognized. Therefore, the production of sewage sludge represents a risk of human health and the environment due to the potential of spreading pathogens. In Mexico, only 5% of the total sewage sludge produced receives a further stabilization treatment. Cheap and effective treatment alternatives are needed in order to guarantee a safe management of this waste. Vermicomposting is an effective treatment option to achieve highest quality stabilization standards and a potential solution for the waste and sanitation problems derived from sewage sludge. The present study analyzes the drivers and barriers for the adoption of this technology and the conditions for its successful implementation.

The stakeholders participating in this study have identified lower capital and operational costs, process simplicity, savings, compliance with current or future policies and laws, and the ease to obtain skilled operators as the main drivers for adopting this technology. The main perceived barriers include uncertainty regarding costs, operational performance and control parameters, as well as the lack of economic incentives, as the main barriers for the adoption of this treatment. In addition, a list of 41 elements that are important for the adoption, diffusion and long term implementation of vermicomposting in sewage sludge was identified and discussed.

Executive Summary

There is a general concern to prevent pollution and health hazards associated with municipal sewage discharges. In the last decade, the average of sanitation coverage in developing countries increased from 30 to 50% (Bauerfeld et al 2008) and it is expected to rise even more in the following years as a result of the implementation of the Millennium Development Goals. The Millennium Development Declaration recognizes the importance of wastewater treatment by seeking "to halve by 2015 the proportion of people without sustainable safe drinking water and basic sanitation" (UN 2008). In Mexico, the sewer system has an installed capacity for providing sanitation to 86.4% of the population and the number is expected to increase to 100% by 2030. Together with sanitation, wastewater treatment plants have to be installed to provide an adequate management and treatment to these discharges. The production of sewage sludge is an unavoidable part of the treatment process. Larger volumes of treated wastewater will require large volumes of sewage sludge and treatment costs. The stage of sludge stabilization is often a neglected part of the wastewater treatment process because of economic reasons. It represents 20%-60% of the overall treatment cost (Spearling and Andreoli 2005) but only provides treatment for 1%-2% of the total treated volume (Tchobanoglous et al 2003). Most developing countries find difficulties affording the capital and operational costs associated with an effective treatment to stabilize the organic content of biosolids (Cardoso and Ramirez 2002). Therefore, a more economic yet effective treatment alternative is needed.

Vermicomposting is an alternative to overcome the previously mentioned problems for the stabilization of biosolids. Vermicomposting is a type of composting process that uses earthworms to produce an organic fertilizer from organic wastes. The technology has proven to efficiently destroy the pathogens from sewage sludge. However, in order to achieve an optimum performance, the treatment depends on a key variable: the worm's survival. The minimum operational controls include the provision of an adequate living environment for the worm, a continuous food supply, and maintenance of temperature, moisture, pH and oxygen levels within an optimal range. Vermicomposting is a cradle to cradle solution that produces a high quality fertilizer, but it can have higher land and labor requirements, as compared with other treatments.

The research evaluated the potential to adopt vermicomposting to stabilize sewage sludge based on the perspectives of five stakeholder groups: current and potential developers, current and potential adopters and government institutions. In general, stakeholders agree on the weight given to some drivers and share heterogeneous opinions on others. There was a consensus among informants that strong drivers are (in descending order of importance) *lower capital and operational costs*, *process simplicity*, *savings, compliance with current or future policies and laws*, and the *ease to obtain skilled operators*. On the other hand, conflicting opinions were found among the informants about the influence of some factors as potential drivers. The debate is mainly centered on *humus market price*, *innovative leadership*, *creating a positive public image*, *landfill avoidance*, and *external recommendations to adopt vermistabilization*. It is also important to mention that *economic incentives* and *successful adoption cases* were evaluated as drivers by all stakeholders except by current adopters. In addition, none of the suggested drivers were evaluated as not influencing.

There was a consensus among the different stakeholders to identify *uncertain costs*, *uncertain performance*, *controlling an unknown process* and *lack of economic incentives* as barriers in decreasing order of importance. However, there is a wide range of opinions for the remaining factors. Contrasting viewpoints are especially important for the factors related to *lack of information* and *higher labor and land demands*. The average scores seem to suggest that current developers and

current adopters have a less negative position on these subjects as compared with potential developers and potential adopters. Therefore, it could be inferred that a deeper knowledge about the treatment might decrease some existing barriers grounded on perceptions.

Furthermore, this research identified 41 elements that are important for the adoption, diffusion and long term survival of the vermicomposting system for sewage sludge. The system is presented in Chapter 5, together with an evaluation of its maturity by development stages. Among the main areas for improvement, the evaluation has identified poor communication channels, certainty about costs and performance, lack of political support for diffusion, and weakness in the distribution channels of the worm hums. The research concludes by determining that vermicomposting is a technology at its infant stage, but with the potential of future development at small scale.

Table of Contents

III

List of Figures

List of Boxes

List of Tables

5

1 Introduction

"Worms are the intestines of the earth."
--Aristotle

1.1 The problem of sanitation and sewage sludge in the global context

There is a general concern to prevent pollution and health hazards associated with municipal sewage discharges. In the last decade, the average of sanitation coverage in developing countries increased from 30 to 50% (Bauerfeld et al 2008) and it is expected to rise even more in the following years as a result of the implementation of the Millennium Development Goals. The Millennium Development Declaration recognizes the importance of wastewater treatment by seeking "to halve by 2015 the proportion of people without sustainable safe drinking water and basic sanitation" (UN 2008). In order to increase the level of sanitation, more wastewater treatment facilities have to be installed. The main purpose of municipal sewage treatment is to prevent health hazards by removing the toxic content from wastewater. The latter produces a solid waste that acts as a sink of the hazardous substances and pathogens present in the sewage discharge. This waste is commonly known as sewage sludge, bio-sludge, or biosolids. An increase in sanitation implies that more sewage sludge will be produced. The disposal of this waste is a matter of concern.

There is a rapid growth in land application of sewage sludge for agricultural purposes. However, biosolids should not be disposed without an adequate treatment to stabilize its hazardous content and make them safe for humans. For the purposes of this research, sludge is considered stabilized when its pathogenic levels are reduced below quality standards defined on national basis, the offensive odors have been eliminated and the potential for putrification has been minimized. However, the stage of sludge stabilization is often a neglected part of the wastewater treatment process because of economic reasons. It represents 20%-60% of the overall treatment cost (Spearling and Andreoli 2005) but only provides treatment for 1%-2% of the total treated volume (Tchobanoglous et al 2003). Thus, most developing countries find difficulties affording the capital and operational costs associated with an effective treatment to stabilize the organic content of biosolids (Cardoso and Ramirez 2002).

There are several proven and commercially available methods for stabilizing sewage sludge (Bauerfeld et al 2005). Liquid sludge (around 1-5% solids) is usually treated using anaerobic digestion, aerobic digestion, lime stabilization or reed beds. On the other hand, dewatered sludge (>10% solids) employs lime stabilization, composting, long-term storage or solar drying. In developed countries, anaerobic digestion is the preferred technology for large treatment works while less expensive processes (e.g. aerobic digestion or lime stabilization) are used for smaller treatment plants (US EPA 2009). The previously mentioned treatment processes work well in developed countries, but present operational problems in developing countries where the regulatory framework for sewage sludge is missing or not being well enforced. Moreover, the technologies for sludge treatment are usually taken from abroad and have to be adapted to local conditions, which increase the cost of capital investment. Thus, a cheap and effective treatment alternative is needed whenever the implementation of a conventional stabilization treatment for biosolids is a challenge.

1.2 The problem of sanitation and sewage sludge in Mexico

As of 2008, the sewer system in Mexico reached 86.4% of the population, and wastewater treatment was available for only 40% of the collected domestic discharge. According to the Mexican National Water Program, the sewer system will available for all the population by 2030, and the wastewater works will provide treatment to 60% and 100% of the domestic discharges by 2012 and 2030, respectively (Mexico., 2008).This implies that more sewage sludge will be produced in the country. This larger volume of waste will also lead to larger treatment costs.

The treatment of sewage sludge is often a neglected part of the wastewater treatment system (Bauerfeld Katrin, Dockhorn Thomas, & Dichtl Norbert, 2008) Approximately, 39.5% of the municipalities in Mexico have a high to very high poverty grade (de Anda, J. & Shear, H., 2008). These are usually small communities that cannot afford expensive treatments and have to minimize operational costs. Therefore, only 5% of all the sewage sludge produced at the wastewater treatment plants receives a stabilization treatment (Cruz-Ojeda, pers. comm.). According to Oropeza (2006) aerobic treatment is the preferred treatment option due to its high removal rate of organic matter, but its bacteriological constituents are not fully destroyed and it requires operators with a minimum technical training (Oropeza, 2006). Another popular treatment alternative in the country is alkaline stabilization. The technology is simple, but it requires a high input of chemicals that increases the operational cost and the biological load can be reactivated (Oropeza, 2006).

1.3 Vermicomposting as an alternative to conventional treatment

Vermicomposting is an alternative to address the problems mentioned above for the stabilization of biosolids. Vermicomposting is a type of composting process that uses earthworms (Neuhauser et al 1988). In its basic form, it is a low cost technology (Khwairakpam and Bhargava 2008) and has proven to be effective for reducing the pathogen content in sewage sludge to meet USEPA Class A and B quality levels (Mitchell 1978, Hartenstein 1981, Loehr et al 1984, Masciandaro et al 2002, Contreras-Ramos et al 2005, Gupta and Garg 2007). The most typically used worm, Eisenia Foetida, contains bactericidal enzymes in its gut that are considered responsible for the reduction of pathogens as the sludge passes through (Pierre et al 1982, Amaravadi et al 1990, Sinha et al 2002). It has also been found that worms adsorb heavy metals in their skins, which explains the reduction in heavy metal concentration in the worm castings (Barrera 2000, Shahmansouri et al 2005). The vermicomposting process has lower energy requirements than the traditional treatments and do not require the input of chemicals. The potential benefits of this technology have captured worldwide interest (Logsdon 1994, Riggle and Homes 1994, Sherman-Huntoon 2000). Albeit attractive, the adoption and diffusion of vermicomposting has not been very successful and the possible reasons for this will be further discussed and studied in this research.

7

1.4 Research statement

The present study follows a qualitative research approach to determine the underlying reasons behind the main stakeholders involved in the process of recycling biosolids that have prevented a greater adoption of vermicomposting. The motivation to do a study of this kind is based on the author's previous experience with this treatment. The author of this thesis has an academic background in Chemical Engineering and professional experience in the wastewater treatment industry. In 2006, the author designed and implemented a vermicomposting process to stabilize sewage sludge at small scale, achieving Class A results based on the Mexican regulation NOM-004-SERMANAT-2002. The previous project was not intended to produce publishable results to be distributed within the scientific community, but to achieve regulatory compliance for an industrial facility. However, several research studies at a laboratory and small pilot scale have also obtained similar results (Mitchell 1978, Hartenstein 1981, Loehr et al 1984, Masciandaro et al 2002, Contreras-Ramos et al 2005, Gupta and Garg 2007). Nevertheless, despite its verified effectiveness and additional advantages, the adoption of this technology has been slow. Thus, the author is interested in understanding the reasons that have prevented a greater diffusion of this technology from the perspective of the main actors involved in the overall management of sewage sludge.

This study is important for three reasons. First, the outcomes of this research can provide a framework for policy makers in order to understand how to support this technology and the main focus areas that need to be encouraged. Second, assessing the potential of vermicomposting adoption would provide useful information for technology developers in order to define marketing and commercialization strategies. Finally, the possible environmental implications of a widespread use of vermicomposting (e.g. bioaccumulation of heavy metals in the food chain, threats to biodiversity and possible changes in the emission of green house gases) have not been fully assessed. The necessity of doing more research on this area would be justified/unjustified by determining the likeliness of a more widespread adoption of this technology.

1.4.1 Aim

The present thesis seeks to identify the current main drivers and barriers for the use of earthworms to stabilize sewage sludge in order to determine the potential for a greater adoption of this biotechnology in the wastewater treatment industry.

1.4.2 Objectives

To assess the current state of vermicomposting adoption.

(1) To identify and evaluate the main drivers and barriers preventing the diffusion of vermicomposting.

(2) To determine the willingness of adopting a vermicomposting system instead of the conventional treatment alternatives.

(3) To determine conditions for adoption of vermicomposting.

1.4.3 Sub research questions

In order to provide a solution for the main research question, this study will respond the following sub-questions:

(4) Are potential adopters aware of the existence of this technology?

(5) What is their position and support given to the adoption of vermicomposting for the stabilization of sewage sludge?

(6) What are the present drivers and barriers for the adoption of vermicomposting as an alternative treatment for sewage sludge?

(7) To what extent does the current system allow the introduction of vermicomposting as a treatment alternative?

(8) Based on the limitations and opportunities found in this study, does vermicomposting have potential to be more widely adopted in the short/long term?

- Yes? Under which circumstances?
- No? Why?

1.5 Methodology

1.5.1 Assumptions

The main assumption that underlines this research is that vermicomposting is an adequate treatment alternative to solve the current sewage sludge management problems. This is based in the fact that earthworms can transform sewage sludge into a valuable organic fertilizer that meets the regulatory requirements and, at the same time, helps to mitigate the generation of greenhouse gases, does not produce a negative impact to the natural ecosystems and minimizes the potential of transferring hazardous constituents to the environment. All that can be achieved with low cost and low energy requirements. Therefore, given this holistic approach, this study assumes that vermicomposting would constitute a viable alternative to conventional solutions for wastewater treatment plants.

1.5.2 Research method and data collection

1.5.2.1 Literature review

This research starts with a literature review about the characteristics of the vermicomposting process (Chapter 2) and the theories explaining the adoption of green technology innovations (Chapter 3). The initial review is used to design the survey questionnaire explained below and to identify the key stakeholder groups involved in the adoption of vermicomposting. A second literature review is carried out later on to get a deeper insight about the information collected and to assess the potential for the diffusion of vermicomposting within the wastewater industry.

1.5.2.2 Semi-structured questionnaire

A semi-structured questionnaire was designed and distributed (in English and Spanish) to answer the sub-research questions by testing the possible reasons for the slow adoption of a new technology as suggested from the literature review. The questionnaire collects the viewpoints from the adopters and developers of technologies for sewage sludge treatment. The format is divided into five sections. Section 1 gathers general information about the informants. Section 2 assesses the level of awareness and trust of the participants. Section 3 uses a 5-point scale to evaluate a list of potential drivers and barriers identified through the literature review, leaving additional space for justifying each score and identifying additional factors not included in the list. Section 4 presents open questions classified by type of informant in order to gather additional information about their context. Section 5 leaves an optional blank space for additional remarks. A sample of the questionnaire format is shown in Appendix 1.

1.5.2.3 Semi-structured interview

A semi-structured interview was used to gather the viewpoints from government institutions via phone conferences. The interviews gather specific information by institution starting from general questions about the institution's attitude towards vermicomposting, the institutional support given to its diffusion, and the end use that the final product should receive. In addition, a similar type of interview was carried out with current vermicomposting developers and current adopters from Mexico in order to understand the present conditions of the system and discuss the answers to the semi-structured questionnaire that required a deeper insight.

1.5.2.4 Data collection

To give answer to the previous research questions, this study is mainly conducted on a stakeholder based approach. The opinions from relevant stakeholders related to the development of this technology are gathered using the previously described semi-structured questionnaire and semi-structured interview. The selection of main stakeholders is based on the previous work by Troshani, who identifies three key actors in the process of breaking the lock that prevents the adoption of a new technology: innovation adopters, innovation suppliers and government (Troshani, I., 2005). Therefore, this study considers the viewpoints from the following informants:

Technology adopters (innovation adopters): includes the current and potential adopters of the technology for non commercial purposes.

Technology developers (innovation suppliers): includes the current and potential developers of the technology. Current developers are the individuals and organizations that design and install vermicomposting facilities for treating sewage sludge, while potential developers refer to the professionals from the current wastewater industry.

Government institutions: this group includes the institutions that promote and regulate the efficient stabilization and management of sewage sludge, its potential application to the land, and the economic incentives supporting these activities.

Current adopters and developers were selected from an exhaustive online search in scientific publications, books, and search engines in order to find those with experience in sewage sludge vermistabilization. The study also considered personal recommendations from confirmed participants regarding relevant potential informants. The initial contact with this group was established via email. The semi-structured questionnaire was delivered via email to those confirming their willingness to participate in this research.

Potential developers and adopters were selected from the directory of the Mexican wastewater sector. They were contacted via email and phone calls, respectively. The previously discussed questionnaire was sent via email to those informants confirming their willingness to contribute to this research. The questions of this format were identical to those answered by current adopters and current developers.

Government institutions were contacted via phone. The contact was initially established with Federal offices, although regional offices were contacted when the latter cannot be established.

1.5.3 Analytical framework

Two different analytical methods are used in this study. The first assesses the information from the questionnaire in order to identify and prioritize the potential drivers and barriers. The second, organizes the viewpoints from informants in order to understand the conditions in which vermicomposting is adopted as a sewage sludge treatment alternative.

a) Evaluation of drivers and barriers

The 5-point evaluation from the questionnaire measures the level of influence for a proposed list of 12 drivers and 12 barriers selected from a literature review. The score given to each factor determines its level of influence on the decision to adopt the technology, being 1 “Not influencing”, 2 “Weak”, 3 “Moderate”, 4 “Strong” and 5 “Very strong”. Then, the information from the questionnaire formats is compiled and classified by stakeholder group. The average evaluation from each group of stakeholders is obtained and the values are plotted in a radar chart. The radar chart tool is selected given its usefulness to compare multiple and unrelated variables in a simple and visual way (Aerni, P., 2002; Kaczynski, D., Wood, L., & Harding, A., 2008). The categories in the perimeter of the chart refer to the items evaluated by each question. The level of influence for each factor is measured by its distance to the center of the graph. The closer the plotted values are to the center, the lower their influence. Conversely, the closer the values are to the outer perimeter of the chart, the higher their importance. This study takes as significant drivers and barriers all those factors with an average score above “3”. Light and dark shadowed regions on the plot separate the “moderate” and “strong” influence zones, respectively, as shown in Figure 1-1.

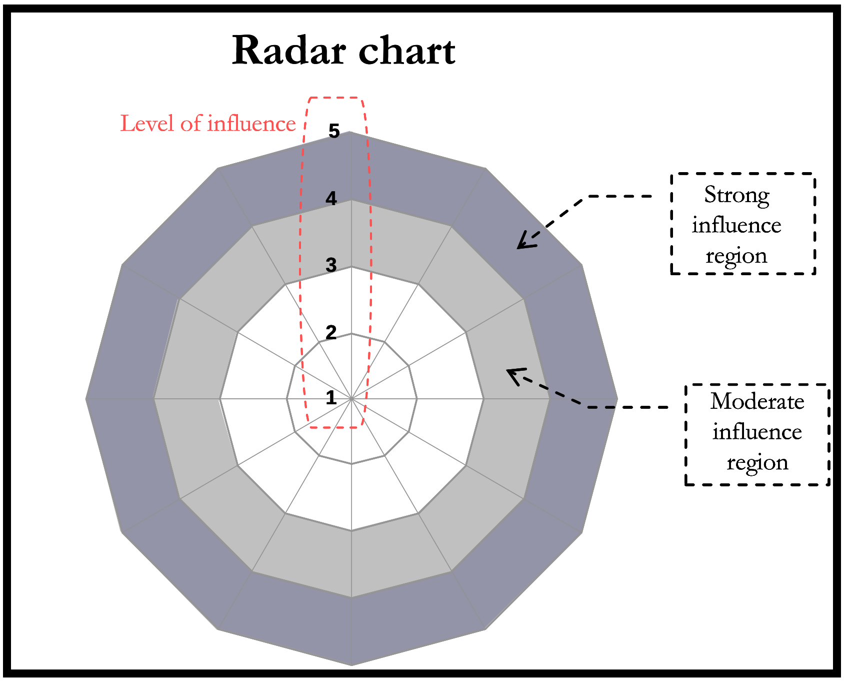

Figure 1-1 Sample radar chart for analysis

In addition, the informants are asked to answer an open question for each of the items evaluated. The latter provides valuable information about their insights that helps to justify the scores provided (Lofthouse et al 2009).

b) Evaluation of the conditions for the adoption and diffusion of vermicomposting

The current and ideal systems in which vermicomposting would be successfully adopted are described based on the stakeholder's viewpoints obtained from the semi-structured interview and semi-structured questionnaire. These systems are compared to evaluate how close this technology is from its successful development. In order to support this comparison, the systems are divided into three stages: sludge production, sludge treatment and sludge disposal. Furthermore, for each stage, the perspectives of the stakeholders are classified into economic, management, political, social and technical factors. The latter classification is proposed by a previous study collecting the experiences of failed and successful composting facilities in Mexico (Rodríguez, M. & Córdova, A., 2006).

The author of this thesis proposes to complement this classification by dividing the system in three stages (sludge production, sludge treatment and sludge disposal) and adding extra space for evaluation, as in Table 1-1.

Table 1-1 Comparison table to evaluate ideal and current conditions

Factor	Stage 1 Sludge production		Stage 2 Sludge treatment		Stage 3 Sludge disposal	
1. Management	Description	Eval	Description	Eval	Description	Eval

	Element 1.1.1	△	Element 1.2.1	✓	Element 1.3.1	△
	Element 1.1.2	✕	Element 1.2.2	△	Element 1.3.2	△
2. Economic	Element 2.1.1	△	Element 2.2.1	-	Element 2.3.1	✕
	Element 2.2.1	✕	Element 2.2.2	✕	Element 2.3.2	✕
3. Political	Element 3.1.1	△	Element 3.2.1	-	Element 3.3.1	✕
	Element 3.2.1	✕	Element 3.2.2	✕	Element 3.3.2	✕
4. Social	Element 4.1.1	△	Element 4.2.1	-	Element 4.3.1	✕
	Element 4.2.1	✕	Element 4.2.2	✕	Element 4.3.2	✕
5. Technical	Element 5.1.1	△	Element 5.2.1	-	Element 5.3.1	✕
	Element 5.2.1	✕	Element 5.2.2	✕	Element 5.3.2	✕

1.6 Research scope and limitations

The global research and efforts to promote the exploitation of earthworms has been focused on a variety of organic wastes and climates. This thesis is centered on the study of the factors affecting the adoption of vermicomposting as a treatment alternative for sewage sludge. However, experiences with other types of waste may be used when necessary for illustration or comparison purposes. The application of vermicomposting for stabilizing sewage sludge has been considered in several countries. Industrial vermicomposting is mainly developed in the United States, Australia, Canada, and Europe, whereas extensive systems are being adopted in Mexico, China, Cuba and India. Despite the global relevance of the topic, the study is geographically restricted to a single country due to time limitations. The country elected for this research is Mexico. The latter choice is based on the author's familiarity with the waste management system, policies and regulatory framework of this country.

The adoption of an innovation technology involves the creation of a new system in which several actors interact. Given the limited time framework, this thesis will focus on the five key actors: current developers, current adopters, potential developers, potential adopters, and government institutions. The characteristics defined for the target groups restrict the information obtained by this study. The development of vermicomposting for sewage sludge is a relatively infant technology. There are not many implementation cases to study and the existing ones have received little promotion. Thus, current developers and adopters of the treatment for sewage sludge are scarce and not easy to contact. In consequence, the information shortage initially motivates a global search in this study. In contrast, potential adopters and potential developers are abundant. Potential developers can be any individual or organization designing WWTP. Potential adopters can be any public or private organization that owns and operates a sewage work. The latter is not considered in this study and the former is restricted to a small sample. There are 2,450 municipalities in the country, but only few of them are contacted via phone calls due to the limited time framework for this study following two criteria: regional GDP (high and low) and climate (arid and tropical). The former is assumed as an indirect indicator of the municipal budget to invest in sewage sludge treatments, while the latter indicates different operational conditions that may affect the worm's adaptation and performance. Finally, the interviews with government institutions exclude policy makers, inspection bodies, Bank of Mexico, Ministry of Economy and other actors providing grants and credits for the implementation of full operation projects.

13

1.7 Outline of the study

The present thesis is structured in six chapters. Chapter 1 introduces the reader to the research problem and presents the methodology used in this study. Chapter 2 provides a basic background on vermicomposting, giving special emphasis on the main operational parameters that shall be controlled. Chapter 3 presents a literature review on the drivers and barriers for the adoption of green technologies, based on the theories that explain the adoption and diffusion processes for innovations. Chapter 4 the perceived main drivers, barriers and theoretical potential for the adoption of vermicomposting as a treatment alternative to stabilize sewage sludge. Chapter 5 compares the current conditions of the system against an ideal model proposed by the stakeholders and the literature review in order to determine the current potential for developing a successful and long term vermicomposting system. Chapter 6 summarizes the main findings of this study and presents general recommendations. The links among these chapters are shown in Figure 1-2.

2 Vermicomposting in sewage sludge

2.1 Introduction

The present chapter starts by briefly reviewing the management of wastewater and sewage sludge, as well as the use of conventional treatment technologies, in the Mexican context. The rest of the chapter is devoted to a literature review on what is currently known about this technique: its main characteristics, operational controls, performance, and environmental implications. The chapter concludes with a summary of the main technological aspects that shall be kept in mind in order to meet the objectives of this research.

2.2 The problem of sanitation in Mexico

2.2.1 Wastewater treatment

As of 2008, the sewer system in Mexico reached 86.4% of the population, and wastewater treatment was available for only 40% of the collected domestic discharge. According to the Mexican National Water Program, the system will be expanded to provide sanitation to all the population by 2030, and the wastewater treatment works will provide treatment to 60% and 100% of the domestic discharges by 2012 and 2030, respectively (Mexico, 2008). As shown in Figure 3-1, the main treatment processes adopted in the country are activated sludge (49.19%), stabilization ponds (17.49%) and primary advanced treatment (10.17%). All of them produce a continuous output of sewage sludge that has to be stabilized to reduce its potential health and environmental hazards. The treatment of sewage sludge represents 20%-60% of the overall treatment cost but accounts for 1%-2% of the total treated volume (Bauerfeld Katrin et al., 2008). Due economic limitations to finance the construction of expensive facilities, 76.7% of the wastewater works in the country adopt low-cost technologies (de Anda, J. & Shear, H., 2008). Therefore, effective and cheap technologies have to be considered as an alternative when conventional sewage sludge treatments are not a suitable option.

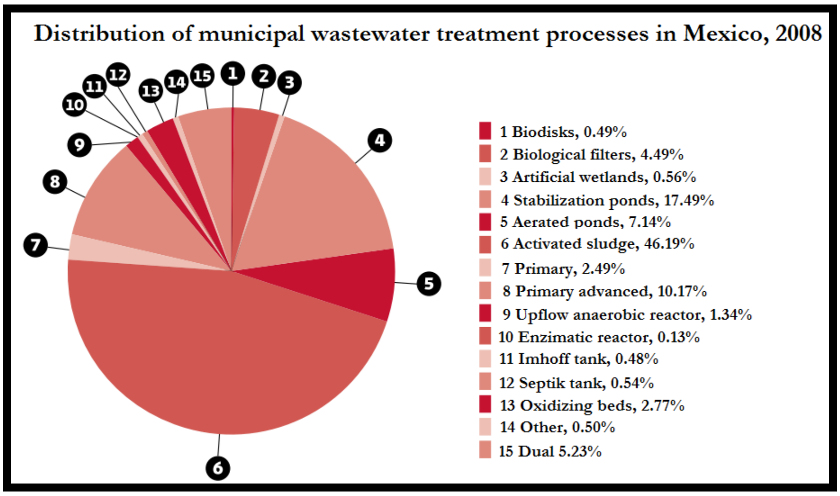

Figure 2-1 *Distribution of municipal wastewater treatment processes in Mexico, 2008*
Source: (Comisión Nacional del Agua, 2010)

2.2.2 Sewage sludge management and treatment

The treatment of sewage sludge is an unavoidable part of the wastewater treatment process and an essential part of an adequate sanitation system. The cost of the conventional stabilization alternatives is high and in many cases their performance is subject to the implementation of complex operational controls. Consequently, the treatment of sewage sludge is usually a neglected part of the complete sanitation system (Bauerfeld Katrin et al., 2008). In Mexico, only 5% of the total sludge production receives a further treatment (pers. comm. Cruz-Ojeda). Above 30% of these facilities are small wastewater treatment plants with a treatment capacity below 60 liters per second (Cardoso, L. & Ramírez, E., 2002). Due to its potential to concentrate toxic substances, the Mexican regulation NOM-052-SEMARNAT-2005 requires a toxic ecological characterization of the waste before its final disposal. The final composition and produced volume of sewage sludge varies depending on the selected treatment method, but typical toxics in the sludge include industrial chemicals and by-products, pesticides, herbicides, and household products (Bauerfeld Katrin et al., 2008).

2.2.3 Conventional stabilization processes

The most popular sludge treatments in Mexico are anaerobic digestion, aerobic digestion, lime stabilization, solar drying and, to a lower extent, composting (Oropeza, 2006). Aerobic treatment is the preferred treatment option by most of the small-scale sewage works due to its high removal rate of organic matter (Jiménez, B. & Wang, L., 2006; Tchobanoglous & Metcalf & Eddy., 2003). However, the bacteriological constituents are not destroyed (pers. comm. Cruz-Ojeda). Larger scale treatment facilities prefer anaerobic digesters; sometimes accompanied by biogas recovery (Oropeza, 2006; Tchobanoglous & Metcalf & Eddy., 2003). Anaerobic digesters can eliminate the pathogenic characteristics when operated under thermophilic conditions. However, due to the high-energy requirements, digesters are kept at mesophilic conditions (<35°C) in which pathogens are not being destroyed (pers. comm. Cruz-Ojeda). Alkaline stabilization is an easy and simple method for temporarily reducing the potential vector attraction, but it requires a high input of chemicals and will not eliminate the biological load (Tchobanoglous & Metcalf & Eddy., 2003). Since most of these treatments do not reach effective levels of pathogen stabilization, its application to the land could produce environmental and health risks associated with the spread of pathogens. According to Le Blanc (2008), the selection of an adequate stabilization technology should also consider best management practices. He recommends the adoption of stabilization processes with low energy requirements that would help to reduce or mitigate the generation of greenhouse gases, do not produce a negative impact in the natural ecosystems, and would minimize the transfer of potential hazardous constituents to the environment (LeBlanc, 2008)

2.3 Vermicomposting sewage sludge

Vermicomposting is an alternative to overcome the problems mentioned for the stabilization of biosolids. The use of vermicomposting in sewage sludge is known as vermistabilization. Loehr et al (1985) defines vermistabilization as "the stabilization of organic wastes using earthworms" (Loehr, E.F. Neuhauser, & Malecki, 1985). The breakdown of organic matter by earthworms has been long known. Research on this field can be traced back to Darwin (Darwin, 1881). In modern times, global research and efforts to promote the exploitation of earthworms in order to process sewage sludge started in the 1970s (Edwards 2004). In its basic form, it is a low cost technology (Khwairakpam and Bhargava 2008) and has proven to be effective for reducing the pathogen content in sewage sludges to meet USEPA Class A and B quality levels (Mitchell 1978, Hartenstein 1981, Loehr et al 1984, Masciandaro et al 2002, Contreras-Ramos et al 2005, Gupta and Garg 2007). Its goal is to obtain a fast and efficient transformation of sewage sludge to minimize the pathogenic content. The latter is achieved through the reduction of volatile solids, which reduces the probability of putrefaction (Edwards, 2004).

The treatment produces an organic fertilizer known as vermicompost, worm humus or worm castings. The worm humus is a light and soft product with a dark brown color and earthly-like odor. Its chemical composition is variable and depends on the characteristics of the raw material and the operational conditions. However, different studies indicate that worm humus has a better quality than conventional compost. It has more humic substances, microorganisms and nutrients nez Cerdas, 1996), and its enzymatic and bacteriological content is higher (Capistrán, Aranda, & Romero, 2001; Edwards, 2004; Reines Alvarez, 1998). It also increases the porosity of the soil, and allows a better air and drainage flow guez, M. & Córdova, A., 2006). Thus, worm humus can be used as soil amendment to increase yields and control erosion as it has been proven that it improves the quality of sandy and loamy soils (Reines Alvarez, 1998).

The vermicomposting process has lower energy requirements than the traditional treatments and do not require the input of chemicals. The potential benefits of this technology have captured worldwide interest (Logsdon 1994, Riggle and Homes 1994, Sherman-Huntoon 2000). Albeit attractive, the adoption and diffusion of vermicomposting has not been very successful and the possible reasons for this will be further discussed and studied in this research.

2.3.1 Earthworm basic knowledge

There are several types of earthworms that can be used for vermistabilization. Suitable species for organic waste degradation are *Eisenia Foetida*, *Eisenia Andrei*, *Eudrilus eugeniae*, *L. Rubellus*, *Dendrobaena*, *Perionyx excavatus* and *Perionyx hawayana* (Edwards, 2004). The most commonly used earthworm for vermicomposting is *Eisenia Foetida* (Capistrán et al., 2001; Edwards, 2004; Martínez Cerdas, 1996; Reines Alvarez, 1998; Rodríguez, M. & Córdova, A., 2006). It can be naturally found underground, but large quantities are also commercially raised by worm breeders (Recycled Organics Unit, 1999). A study comparing five earthworm species (*Dendrobaena veneta, Eisenia Foetida, Eudrilus eugeniae, Perionyx excavatus* and *Pheretima hawayana*) demonstrated that *E. Foetida* achieved the highest growth and reproduction rate (Loehr et al., 1985). It is also demonstrated that *E. Foetida* can achieve a greater reduction of volatile solids as compared with other earthworms (Edwards, 2004). Furthermore, this earthworm contains bactericidal enzymes in its gut that are considered responsible for the reduction of pathogens as the sludge passes through (Pierre et al 1982, Amaravadi et al 1990, Sinha et al 2002).

E. Foetida hatches from its cocoon in 3 weeks at 25°C and starts a fast growth rate three weeks after its birth (D. L. Kaplan, E. F. Neuhauser, & R. Hartenstein, 1980). Its growth and reproduction rates decrease when the worms exceed the carrying capacity of the media (Roy Hartenstein, Edward F. Neuhauser, & David L. Kaplan, 1979). Nevertheless, earthworms can double their population in 60 to 90 days if optimum operational parameters are met. (Reines Alvarez, 1998).

Figure 2-2 Earthworm "Eisenia Foetida".

2.3.2 Operational parameters

The performance of the treatment depends on the worm's survival at optimum environmental conditions. In order to meet its basic needs, the worm requires a hospitable living environment (bedding), a continuous food source and adequate moisture, oxygen and temperature controls.

Bedding: The bedding provides protection and nourishment to the worm. This is where the worm lives. An ideal bedding material provides protection, moisture control and allows the flow of oxygen. The mixture of sewage sludge with this bulking material accelerates the decomposition rate (Edwards, 2004). There are several materials reported as adequate beddings for the earthworms that include manure, oyster shells, and sawdust (Kwon, Lee, & Yun, 2009). The selection of the bedding material depends on the local resources available and their capacity to hold moisture from the sludge to allow the oxygen flow. Figure 2-3 (left hand side) illustrates the importance of good bedding. Worms will not degrade the sludge when the bedding fails to provide hospitable conditions.

Figure 2-3 Decomposition of sewage sludge by earthworms. Unprocessed sludge (left-hand side) results from the lack of porosity due to insufficient bedding material.

Food source: Earthworms are voracious eaters and will also eat the bedding as they make their way through the waste. As a rule of thumb, they could eat their weight per day under optimal conditions (Capistrán et al., 2001). In general, Mexican sewage sludge is suitable for vermicomposting and would make an excellent food source for the worms due to its high nutritional value (Capistrán et al., 2001). However, its high moisture content may require the use of an extra bulking material in order to absorb excess of water and increase the porosity of the substrate to facilitate the movement for the worm. Changes in the composition of the sludge affect the worm's actions. An in-situ vermicomposting study demonstrated that worms reject fresh anaerobic sludge and tend to abandon the substrate (D.L. Kaplan, R. Hartenstein, E.F. Neuhauser, & Malecki, 1980; Masciandaro G., Ceccanti B., & Garcia C., 2000). However, anaerobic sludge can become suitable for the worms if dewatered, aerated and with redox potential above 250 mV (D.L. Kaplan et al., 1980). Vermistabilization of aerobic sludge achieves a quick odor disappearance and a fast reduction in pathogenic microorganisms and helminth eggs (Edwards, 2004). The nutritional value of activated sludge decreases with time for the earthworm. Activated sludge aged for more than 30 weeks does not provide a suitable substrate to allow the earthworm growth (R. Hartenstein & E. Neuhauser, 1985). In aerobic sludge from drying beds, the use of earthworms can faster the decomposition and enhance the final characteristics of the stable sludge by increasing its potential to absorb water (R. Hartenstein & E. Neuhauser, 1985), double the destruction rate of volatile solids (E.F. Neuhauser & Callahan, 1990).

Sewage sludge can act as the sink of many toxic substances. The main toxic chemicals from the sewage sludge can be detergent cleansers, industrial chemicals, pesticides and tannins. Although worms are generally tolerant to a high range of these pollutants, heavy metals or chemical contamination could disrupt the process (Edwards, 2004). Sludge with high concentrations of ammonia and inorganic salts are toxic to *E. Foetida* (Edwards, 2004). Soluble salts above 0.5% in excess can be lethal, as well as ammonium acetate in a concentration of 0.1% (D.L. Kaplan et al., 1980). Inorganic chemicals used to coagulate sludge at the wastewater treatment plant are not toxic at the typical loads used in the sewage works (D.L. Kaplan et al., 1980). However, pre-composting reduces or eliminates these threats, but also decreases the end value of the product (Gunadi et al 2002).

Temperature: Knowledge of the temperature effects on worms is useful to determine treatment efficiencies and reproduction rates[1]. Under freezing conditions, only cocoons may remain viable for several days (Edwards, 2004). Above 0°C and below 10 °C, worms do not consume as much food but can survive, although they will not reproduce (Edwards, 2004). Reproduction rates are stimulated around 20°C (Loehr et al., 1985). The optimum growth of the earthworm occurs in the range 20 to 25°C and reduces as the temperature increases around 30°C (Loehr et al., 1985). At temperatures above 35°C, the worms will leave the bedding or will quickly die if they cannot escape (Edwards, 2004).

Moisture: Excessive and insufficient moisture can affect the worm's growth (Edwards, 2004). The optimum moisture range for vermicomposting has been determined at 70 to 85%, with a tolerance range of 60 to 90% (Edwards, 2004; D.L. Kaplan et al., 1980). As moisture increases, worms will gain weight. Therefore, this parameter can be used to control the biomass of the system. Moisture is also important to prevent predators. Low moisture levels may result in the presence of ants, a natural predator of the earthworm (Capistrán et al., 2001).

Oxygen: Worms need a good oxygen flow within their substrate because they breed through their skin. Oxygen can be supplied using mechanical devices or a good bedding material (Capistrán et al., 2001). A bedding material with good porosity will allow the movement of the worms through the substrate. As the worm makes its way through the waste, its oscillating movement will provide the necessary oxygen supply for the process. In addition, oxygen is also responsible for maintain aerobic degradation reactions (Edwards, 2004).

pH: One of the main advantages of *Eisenia Foetida* is its ability to adapt to a wide range of pH levels. While the optimum pH is 7.5-8*, E. Foetida* will tolerate a pH range from 5 to 9 (D.L. Kaplan et al., 1980).

2.3.3 Processing methods

According to Edwards (2004), the basic principle common to all the processing methods consists in spreading sludge in thin layers of 10 to 15 cm. Worms will migrate from the bottom layers upwards to colonize the fresh substrate. Once the material is fully digested, a new layer of sludge is set and this basic procedure shall be repeated until the pile of castings reaches a height convenient to the vermicomposter (Edwards, 2004). This procedure allows a uniform degradation of the organic matter. Worms are separated from the castings before the harvest by migration. They are starved for some days and later put into contact with fresh substrate. Worms will migrate to the new feedstock in two or three days. That can be done using food traps or designing the beds with open gates to allow the migration. The

[1] Temperature controls refer to the temperature inside the bedding material.

recently harvested castings are dried up to 30 to 50% moisture in order to maintain the bacterial population, viable cocoons and small worms. Finally, the humified material is sieved to separate unprocessed waste and obtain a uniform particle size with specific porosity. Liquid humus can be obtained from the moisture leaks. As the water flows downwards, it dissolves nutrients and minerals. This product can also be used as fertilizer. Some odor may be present during the application of sewage sludge to the beds, but worms are able to control it quickly (Capistrán et al., 2001).

Edwards (2004) mentions four basic methods for processing waste through vermicomposting: windrows, beds, wedge systems and bio-reactors. However, no information was found about the wedge systems in additional literature. Therefore, this method will not be described among those presented below.

2.3.3.1 Windrows or waste heaps

In this method, wastes are piled on the ground, usually outdoors. In some cases, a liner is used to prevent contact with the ground. The capital investment is low, but the procedure requires long residence time (6-12 months), large land requirements and it is labor intensive. In addition, this system produces a lower quality product since nutrients are lost from evaporation and leaching (Edwards, 2004). There are several types of windrows, the most common being batch fed static piles and continuous flow top-fed windrows. While the former mixes worms and waste in a batch regime until the material is fully decomposed, the latter continuously adds layers of waste after initial bedding has been set (Larroche, 2008). Windrows are the most traditional and predominant vermicomposting method in Mexico for the large variety of organic wastes being vermicomposted (Aranda, pers. comm.). Wastes are piled on the ground up to a maximum height of 50 cm (Martínez Cerdas, 1996).

2.3.3.2 Beds

This is the preferred method for composting sewage sludge. Wastes are spread in long rectangular-shaped rows build with a rigid material (e.g. concrete). A polyethylene liner may be used when the bottom is in direct contact with the ground. This design avoids the migration of the worm and allows the potential recovery or liquid humus. The efficiency of the treatment increases since this method allows an operation with heights slightly above 1 meter (Martínez Cerdas, 1996). The average residence time of this treatment is 3-4 months (Edwards, 2004).

Figure 2-4 Windrows

Figure 2-5 Concrete vermicomposting beds.

21

2.3.3.3 Bioreactors

The selection of the processing method depends on finding a balance between the required capital investment (mechanization) and operational cost (labor and time). Although the basic principle is the same, different treatment methods (with different designs) achieve different levels of performance. Bioreactors utilize a mechanized operation to reduce land and labor requirements. In addition, the treatment can achieve residence times of 45 days (Edwards, 2004)

2.3.4 Performance

The effectiveness of the technology depends on the correct control of the operational parameters, but also on an adequate design. Depending on its design vermicomposting can be a moderately high land and labor demanding operation (as compared with other treatments). Studies have been carried out to determine the conditions to increase its performance. Those include mixing different worm varieties (polyculture) and combining the treatment with other processes. One study comparing a polyculture and monoculture earthworm process demonstrated that there are not significant differences between these treatments (Loehr et al., 1985). The effectiveness of combined composting and vermicomposting systems has been demonstrated in laboratory scale projects. Combined systems perform better and obtain higher reduction of volatile solids, meeting pathogen reduction requirements with a shorter stabilization time. The latter was demonstrated at the laboratory scale with a mixture of sewage sludge and paper mulch (Ndegwa & Thompson, 2001). A subsequent study used a mixture of sewage sludge and sawdust. The experiment achieved the highest reduction in volatile solids using a combination of thermophilic composting followed by vermicomposting to obtain EPA Class A biosolids and a better performance in the combined systems than their individual performances (Alidadi, Parvaresh, Shahmansouri, Pourmoghadas, & Najafpoor, 2007).

2.3.5 Implementation of vermicomposting

There have been past attempts to develop vermicomposting projects for sewage sludge in the United States and the UK (Edwards, 2004). The projects have failed for different reasons. In the 1980s, a four tones/week facility was installed in Lufkin, Texas (Edwards, 2004). The process did not survive since all the earthworms died in a particular hot summer (Budzich, pers. comm.). A second facility installed in Ontario, Canada had to close its operations when the application rate of worm humus to the ground exceeded the allowed concentration of heavy metals within 45 years (Recycled Organics Unit, 1999). A large-scale project in Philadelphia was carried out by one of the informants, who report that the facility had to be discontinued due to a significant expansion the wastewater treatment process that required excessive land requirements for the vermicomposting operation (Budzich, pers. comm.) Little information is available in the literature about other failed experiences. Ontario Canada; Bird and Hale 1982: used industrial sludge, applied to the ground at a rate the increased the concentration of heavy metals within 45 years. In Mexico, pilot testing and implementation are recent, which does not allow a review of the success of these treatments.

2.3.6 Vermicomposting comparison with conventional treatments

The decision to adopt vermicomposting shall consider a cost-benefit evaluation. Although the technology can produce a highly rich organic fertilizer, it also presents disadvantages related to design demands. Table 2-1 presents a comparison of the main treatment methods in Mexico, followed by an evaluation by technology shown in Table 2-2.

Table 2-1 Comparison of sewage sludge stabilization technologies in Mexico.

Treatment	Description	Operational conditions	Basic equipment	Pre-treatment	Capital investment*	Typical final use
CLASS A SEWAGE SLUDGE STABILIZATION						
Aerobic digestion	Aerobic degradation of organic matter by bacteria at mesophilic temperatures.	13-17 days at 35°C, 1-2 ppm of dissolved oxygen	Aerobic digestor, blowers, air diffusors, pumping system	Thickening	2,000,000 MXP	Fertilizer, soil amendment, landfill
Incineration	Thermal destruction of organic matter at high temperatures; potential energy recovery	> 60°C at least for 20 minutes; or 1000°C for inmediate destruction	Incinerators, air pollution control equipment	None	n.a.	Energy recovery, ashes are incorporated to cement (if destroyed in kilns) or sent to landfill
Aerobic digestion (thermophilic)	Aerobic degradation of organic matter by bacteria at thermophilic temperatures.	10 days at 55°C-60°C, 1-2 ppm of dissolved oxygen and mixing	Tanks, gas control system, skimmer, blower and diffusers, agitation system.	Thickening	5,881,200 MXP	Fertilizer, soil amendment, landfill
Vermicomposting	Aerobic breakdown of organic matter using worms	Depends on the design	Worm beds, irrigation system, shreeder, sieve	Dewatering (filter); pre-composting is optional.	?	Fertilizer, soil amendment, landfill; energy recovery
CLASS B SEWAGE SLUDGE STABILIZATION						
Treatment	**Description**	**Operational conditions**	**Basic equipment**	**Pre-treatment**	**Capital investment***	**Typical final use**
Anaerobic digestion	Bacterial degradation of organic matter in the absence of oxygen at mesophilic temperatures.	15 days at 35°C-55°C, or 60 days at 20°C	Closed digestor, agitation system, methane recovery system, pumping system	Thickening	57,286,223 MXP	Fertilizer, soil amendment, landfill; energy recovery
Solar drying	Solar dying on sand or concrete beds	3 months at temperatures above 0°C	Drying beds, sludge feeder and distribution system	Dewatering (filter)	1,123,000 MXP	Fertilizer, soil amendment, landfill
Lime stabilization	Sludge is mixed with lime to raise pH levels	pH = 12 for at least 30 minutes	Sludge storage, chemical dosification and mixing systems; particle control equipment.	Dewatering (filter)	2,594,466 MXP	Fertilizer, soil amendment, landfill
Composting (windrow)	Aerobic decomposition of organic matter by bacteria and fungus at thermophilic temperatures; requires a bulking media.	Above 56°C for at least 15 days; turn 5 times	Truck, blowers, shredder, sieve	Dewatering (filter)	1,135,816 MXP	Fertilizer, soil amendment, landfill
Composting (aerated static pile)		55°C or above for at least 3 days	Truck, blowers, shredder, sieve	Dewatering (filter)	1,689,399 MXP	Fertilizer, soil amendment, landfill

* Based on a Mexican facility for 300,000 people
** MXP: Mexican peso; 1 USD = 12.83 MXP (Exchange rate in May, 2010).
Source: Adapted from (Instituto del Agua del Estado de Nuevo León, 2008)

Table 2-2 Comparison of investment costs based on a medium-scale wastewater treatment facility for 300,000 people.

		Investment cost	*Operational cost*	*Labour requirement*	*Land requirement*	*Training needs*	*Energy recovery*	*Stabilization level*
Treatment alternatives	Aerobic digestion	△	△	✓	✓	X	X	△
	Anaerobic digestion (mesophilic)	X	△	✓	✓	X	✓	△
	Anaerobic digestion (thermophilic)	X	X	✓	✓	X	✓	✓
	Composting	✓	✓		X	△	X	△
	Incineration	X	X	✓	✓	X	✓	✓
	Lime stabilization	△	△	✓	△	△	X	△/X
	Solar drying	✓	✓	✓	X	✓	X	✓/ △
	Vermicomposting	✓	✓	△/X	X	△	X	✓
Nomenclature	✓	< 2 million pesos	Low	Low	Low	None	Yes	Class A
	△	2-5 million pesos (MXP)	Moderate	Moderate	Moderate	Some technical knowledge	-	Class B, C
	X	> 5 million pesos (MXP)	High	High	High	Special technical knowledge	No	Below Clas C

Source: Adapted from (Instituto del Agua del Estado de Nuevo León, 2008)

From Table 2-2, it can be seen that the implementation of vermicomposting closely competes with solar drying and the other composting processes.

2.4 Conclusion

The performance of the treatment depends on finding the optimal conditions to guarantee the worm's growth, reproduction and survival. Maximum productivity is achieved in aerobic sludge at temperature range 20 to 25°C and moisture control 70 to 85%. Although worm can resist the presence of several toxic chemicals, excessive concentrations of ammonia and inorganic salts must be prevented, as they can be lethal. The selection of the ideal vermicomposting method shall consider a balance among the investment cost, desired residence time and land available.

3 Theoretical background on technology adoption theories

3.1 Introduction

This chapter presents a literature review of the theories exploring the adoption process of an innovation, and the main potential drivers and barriers for its adoption. The purpose of this chapter is to provide a baseline understanding of the possible underlying reasons behind the slow adoption of vermicomposting to stabilize sewage sludge. The chapter concludes with a list of potential drivers and barriers that might be influencing in the decision to adopt vermicomposting. Those factors will be later utilized to elaborate the semi-structured questionnaire described in Chapter 1 and Appendix 1 in order to support the identification of drivers and barriers by stakeholder. In addition, the theories presented in this chapter may be used to support the viewpoints expressed in Chapter 4 and Chapter 5.

3.2 General theories on technology innovation and diffusion

The selection of a specific technology for utilization by an individual is known as "adoption". The term "innovation" refers to the adoption of a completely new technology. The "diffusion" of the technology occurs when it is spread to general use and application. Several authors have analyzed the process of adoption and diffusion of new technologies within organizations (Khedr, 2008). The latter has resulted in several models trying to explain the adoption and diffusion processes. Rogers (2003) explains adoption over time as a lifecycle model of five stages characterized by different types of adopters. The lifecycle starts with the discovery of an innovation by a group of innovators or researchers that are driven by the creation of knowledge. Later, early adopters embrace this technology when they recognize its potential to solve a particular need. Once the effectiveness of the technology is proven by the early adopters, it starts to become adopted by a group of "early majority" that is looking for a change but are afraid to take risks. The subsequent two stages involve its adoption by a late group of conservative adopters and by those that are antagonist to the new technology and may never decide to use it (Rogers, 2003). According to Moore (1991), the diffusion stage starts when the initial resistance of the "early majority" is broken and they decide to adopt the technology. Therefore, in order to diffuse a technology, it is important to understand the mechanisms that drive its early innovation and early adoption.

3.2.1 Technology innovation

Technology innovation involves the complete process from the discovery of the initial idea that may become a new development until its market commercialization (Maxwell, 2009). The initial stage of this process is characterized by a slow invention-induction-development period that will be preceded by a rapid adoption stage once the technology reaches its "innovation tipping point" (Maxwell, 2009). The duration of this initial stage varies significantly depending on the technology. For instance, modern software developments can reach the "tipping point" in months; while technologies developed within markets that are more conservative will slowly move towards its adoption in a number of years or decades (Maxwell, 2009).

It is widely believed that early adopters are the driving force behind many innovations (Lettl & Gemünden, 2005). Users become innovators when the existing technology does not satisfy their needs and the technology developers do not offer alternative solutions (Baldwin, Hienerth, & Hippel, 2006). Their participation changes over time (Raasch, Herstatt, & Lock, 2008). Innovation from early adopters is high when the technology is at an immature stage (Baldwin et al., 2006) because the lack of standardization in the design allows changes until it fits the user's particular needs (Raasch et al., 2008). At this point, early adopters receive a greater support from small-scale developers because then can deal with the installation of a flexible design (Braun & Herstatt, 2007). In addition, early adopters prefer to risk with simple technologies but their participation over time start to decline as the technological complexity increases (Baldwin et al., 2006). Generally, the complexity of the system is proportional to its scale size (Jofre, Tsunemi, & Morioka, 2003). Thus, early adopters are expected to succeed innovating at small-scale processes. Finally, the participation of early adopters declines as the technology becomes diffused in the market by big technology developers (Raasch et al., 2008).

3.2.2 Technology adoption and diffusion

There is an inertia within the organizations that makes them resist to any change due to fear of possible future disruptions if conventional technologies and practices are replaced (Aylward, 2006). This is a form of risk avoidance (Aylward, 2006) that creates barriers for more sustainable innovations (Foxon & Pearson, 2008). Once a technology has proven successful, institutions become reluctant to experiment elsewhere (Pierson, 2000) and the more historically successful, the higher their risk aversion (Aylward, 2006). Likewise, the more adopters, the more attractive the technology becomes (Aylward, 2006). Arthur explains this phenomenon as an interaction among three elements: markets, technologies and political decision-making. The three elements co evolve together to create locks that prevent future developments (Arthur, 1989). These locks cannot be broken by the introduction of a new and technology, but by a balance between the market and the attractiveness of the new technology to the users. Potential adopters will migrate to a new technology if it becomes more attractive (Dolfsma & Leydesdorff, 2009). Raasch et al (2008) suggest that it is the user's dissatisfaction with existing technologies what promotes the development of innovations. Potential developers are not involved at an early stage; often do not understand the need of adopters for innovation. It is difficult for them to have access to this abstract and intangible information about their clients (Raasch et al., 2008).

Adopters have proven to be the driving force behind many innovations (Lettl & Gemünden, 2005). Breaking the lock depends on users, not on developers. Government also plays an important role in breaking this lock. A strategic political decision can affect the dynamics of the technology diffusion (Dolfsma & Leydesdorff, 2009). Thus, institutional support is necessary to promote the adoption of more sustainable systems (Foxon & Pearson, 2008).

The adoption and diffusion of a new technology can be also interpreted as knowledge, persuasion, decision, implementation and confirmation (Rogers, 2003). Established communication channels facilitate the spread of the knowledge (Raasch et al., 2008). The study by Raasch demonstrates that early adopters are willing to share their knowledge freely with other potential users (Raasch et al., 2008). Once the potential adopters (early majority) receive the information about the new technology, they must be persuaded about its potential benefits in order to adopt it. As the technology becomes more popular, more potential adopters become interested in the innovation. It is at this stage when potential developers become interested in diffusing the new technology.

As the technology becomes more popular, large suppliers will become interested in its diffusion and will try to standardize it in order to decrease production costs and increase the market size (Baldwin et al., 2006). This standardization reduces the flexibility of the initial design and it implies that individual needs from the early adopters could be eliminated from commercial product (Raasch et al., 2008).

Foxton and Pearson (2007) present two innovation models. According to the linear model, an increasing support to research and development will increase the diffusion of clean technologies. This model supports the idea that economic incentives are the most effective mechanism to promote diffusion of a new technology by helping it to reach a specific market. On the contrary, modern theories support non-lineal models that affirm markets are dynamic systems where consequences are often unanticipated. Instead, the non-lineal model approach affirms that innovation results from the interplay of different actors a limited ability to gather and process information for decision-making (Foxon & Pearson, 2008). This interplay involves knowledge flows and market interactions. Thus, non-linear models affirm that innovation and diffusion are dynamic, non-linear and systemic processes limited by the interaction of technology and institutions. While technology is subject to fast change, institutions tend to change relatively slowly (Foxon & Pearson, 2008).

3.3 Drivers and barriers for sustainable innovations

The decision to adopt a new technology depends on several factors that can work as drivers or barriers. Lofthouse et al (2009) identified a list of drivers and barriers for green technology adoption. The main drivers identified in that study include waste minimization and reuse, cost reductions from lower energy requirements, avoidance of landfill, effectiveness in pollution remediation, flexibility of the operation and easiness of the operation (Lofthouse, Bhamra, & Trimingham, 2009). On the other hand, the barriers include higher space requirements, high capital investments or operation costs, uncertainty and difficulties of embracing a new process, lack of expertise, and difficulties of changing the currently existing technology. The relative importance of these factors varies depending on the informant groups being surveyed and their country of origin (Montalvo & Kemp, 2004; Troshani & Doolin, 2005).

The decision of adopting a new technology can also be influenced by several groups with different viewpoints. The adoption and diffusion of an environmental technology is mainly determined by technology adopters and technology developers (Troshani & Doolin, 2005). Current developers can act as a barrier for the development of an innovation (Braun & Herstatt, 2007). However, users profiting from the existing technology may also slow down the adoption (Raasch et al., 2008). There is also a limited influence of regulators in the system (Troshani & Doolin, 2005). According to Montalvo and Kemp (2004), regulators can pressure for improvements in environmental performance but do not have a significant influence on the type of technology adopted (Montalvo & Kemp, 2004). The influence of other pressure groups, such as NGOs, business associations and society has been found negligible (Blackman & Kildeegard, 2004; Montalvo Corral, 2002; Montalvo & Kemp, 2004). Powerful actors with economic power can inhibit the diffusion of an innovation (Foxon &

Pearson, 2008). However, public pressure can work as a complement for regulations (Montalvo & Kemp, 2004). Thus, the main pressure groups for the process of technology adoptions and diffusion are the adopters, developers and regulators.

The main pressure groups give different relative importance to the possible drivers and barriers presented above. Technology adopters stress the importance of economic incentives (Luken & Van Rompaey, 2008), high benefits vs. costs and successful validation of the technology by several early adopters (Troshani & Doolin, 2005). Technology developers and regulators share a similar viewpoint and identify regulations and the high cost of inputs as main drivers (Luken & Van Rompaey, 2008). Although current regulations are not pointed as a driver, the expectation of more stringent regulations in a near future may have some influence (Montalvo & Kemp, 2004). For all the main pressure groups, the most significant barrier was the high cost of implementation and/or operation (Luken & Van Rompaey, 2008). Major changes on currently installed technology, lack of information, lack of expertise, and uncertainty about the new technology performance were also identified as limitations (Adeoti, 2002; Troshani & Doolin, 2005). In addition, Jofre et al (2003) recognize two forces driving the demand for a more sustainable product: cultural and technological factors. The cost of the technology and its functionality can drive or constraint the development of environmental innovations (Jofre et al., 2003).

Adeoti (2002) found that environmental policies were only a driver for those with a strong commitment towards the abatement and prevention of pollution (Adeoti, 2002). Montalvo (2002) states that in developing countries regulations are not an important driver due to the weakness of the regulatory institutions and that their willingness to embrace new technologies depend on perceived risk of capital loss (Montalvo, 2008). The lack of technology is ranked higher in developing than in developed countries, while public pressure is ranked lower as the income of the evaluating country decreases (Luken & Van Rompaey, 2008).

3.4 Conclusion

This section presents the main theories explaining technology innovation and diffusion. Based on these theories, it identifies the main drivers and barriers from a literature review. This identification is a useful starting point for this study. The identified drivers and barriers from this literature review are used to elaborate the semi-structured questionnaire presented in Appendix 1. This questionnaire is distributed as explained in Section 1. Its main purpose is to evaluate the influence of the list of suggested factors in order to determine the main limitations and opportunities of adopting vermicomposting to stabilize sewage sludge. The information gathered from the stakeholders considered in this study is presented as follows in Chapter 4.

4 Stakeholder viewpoints on adopting vermistabilization for sewage sludge

This chapter presents the perceived main drivers, barriers and theoretical potential for the adoption of vermicomposting as a treatment alternative to stabilize sewage sludge. The information presented summarizes the viewpoints from four groups of stakeholders participating in the semi-structured questionnaire described in Section 1.3.2.

Sixty questionnaires were distributed among the informants from four different countries. Table 4-1 presents the statistics about the participation[2]. After an exhaustive global search, this study has found that there are a limited number of possible informants and they are not easy to contact. The latter is *per se* a failure in the system that impedes the broader diffusion of this technology.

Table 4-1 Questionnaire response rate

Description	**Current developer**		**Current adopter**		**Potential developer**		**Potential adopter**	
Origin	International	Mexico	International	Mexico	International	Mexico	International	Mexico
Contacted	14	6	11	7	0	10	0	12
Response	6	5	0	3	0	2	0	3
% participation	43%	83%	0%	43%	-	20%	-	25%

Although Mexican municipal wastewater treatment facilities from different regions and income distribution were contacted, responses were only obtained from medium to large facilities from the North and Northwest regions. These facilities are characterized by the use of conventional treatment technologies such as aerobic digestion and anaerobic digestion with biogas recovery. The latter may not be representative of the current conditions because the majority of the municipalities operate with lower budgets. Nevertheless, their viewpoints are of research interest because, according to the theoretical background presented in Chapter 3, these municipalities would be expected to present the highest reaction against the adoption of this new technology.

4.1 Drivers to adopt vermistabilization

This section summarizes the findings on the drivers that would motivate the adoption of vermistabilization as a treatment alternative for sewage sludge. Figure 4.1 presents a radar chart with the averages from the 5-point evaluation by stakeholders, described in Section 1.3.2. The factors with an average score within the shadowed regions are classified as drivers. Values on the darker region are considered strong drivers, while average scores falling on the lighter zone are considered to have a moderate influence. The vicinity to the outer perimeter

[2] The number of questionnaires delivered and the participation rate may not be statistically representative of the whole population of potential adopters and potential developers. However, given the lack of previous studies on this subject, the limited information gathered in this study may be useful as a starting point for future research.

indicates a greater influence level of the corresponding factor on the decision to adopt the vermistabilization technology.

In general, stakeholders agree on the weight given to some drivers and share heterogeneous opinions on others. There was a consensus among informants that strong drivers are (in descending order of importance) *lower capital and operational costs*, *process simplicity*, *savings*[3], *compliance with current or future policies and laws*, and the *ease to obtain skilled operators*. On the other hand, conflicting opinions were found among the informants about the influence of some factors as potential drivers. The debate is mainly centered on *humus market price*, *innovative leadership*, *creating a positive public image*, *landfill avoidance*, and *external recommendations to adopt vermistabilization*. It is also important to mention that *economic incentives* and *successful adoption cases* were evaluated as drivers by all stakeholders except by current adopters. In addition, none of the suggested drivers was evaluated as not influencing.

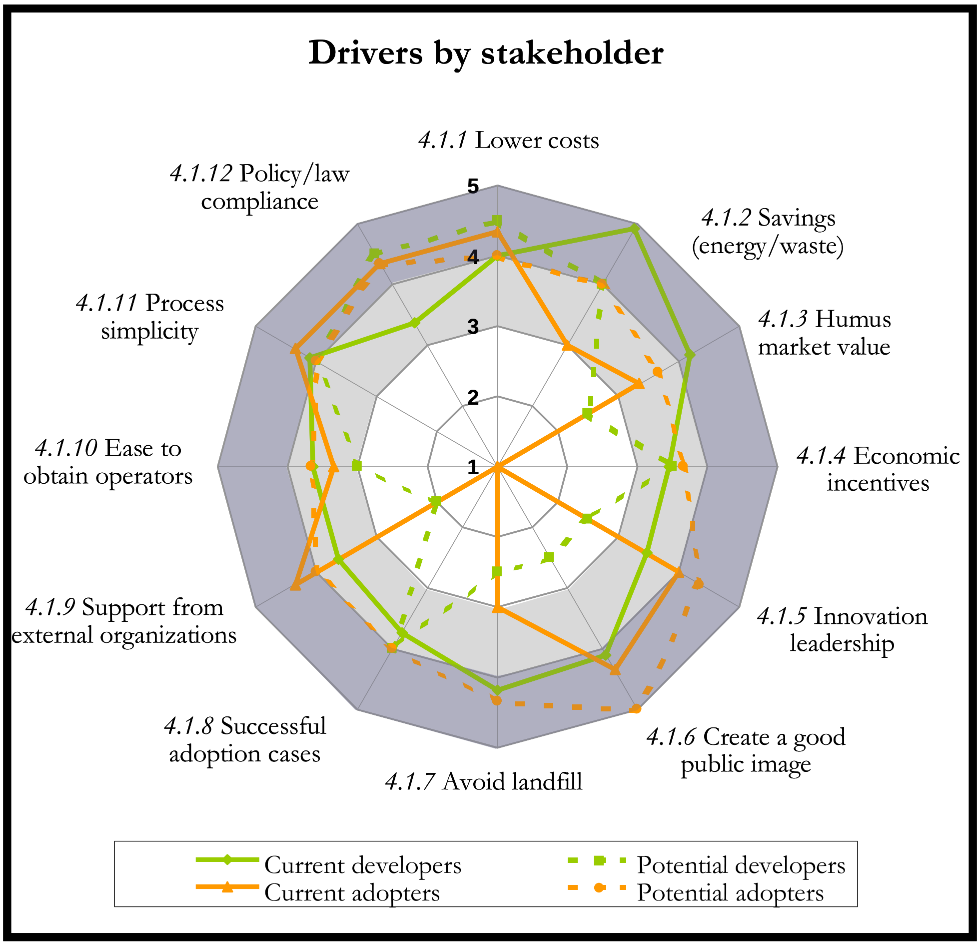

Figure 4-1 Evaluation of drivers by stakeholder

The group of **current developers** identifies *savings* as the strongest driver for the adoption of vermicomposting. However, the evaluation from this group shows a notorious lack of consensus on the rest of the factors (*see* Appendix 1). They also present the widest range in scores among all the participants in this study. The latter might be partly explained by the heterogenic origin of the informants from this cluster, as the group considers participants from different countries. In spite of this, the average scores of their evaluation identified the

[3] Although *savings* in operational costs are considered as an important driver, its evaluation by current adopters was influenced by a low score from one of the informants that represent the viewpoints from a landfill site.

following factors (in descending order or importance) as additional potential drivers with a strong influence: *humus market value*, *avoiding landfill*, *process simplicity*, *creating a good image*, *lower capital investment and operation cost*, *successful adoption cases*, *ease to obtain operators*, and *support from external organizations*. Finally, the group identifies *innovation leadership*, *economic incentives*, and *policy and law compliance* as the factors with a lowest influence.

The group of **current adopters** is comprised of three vermicomposting adopters of different nature: a manufacturing company, an academic institution and a landfill. The latter affirms that the vermicomposting process installed at their site provides treatment to a small share of the organic waste received in the landfill in order to create a positive public image. The other two informants operate a small-scale vermicomposting treatment in order to stabilize the sewage sludge produced at the wastewater treatment plants installed at their facilities. In contrast with the opinion shared by the current developers, the viewpoints in this group do not suggest a unique driving force to adopt vermicomposting. Instead, the decision is based on a combination of several factors that vary depending on the nature of their activities and needs. Except for the landfill site, *potential savings* in the operation were the main driving force identified by current adopters[4]. Other average scores from their evaluation suggest that the group recognizes (in descending order of preference)the *lower capital investment and operational costs*, *creating a good public image*, *policy and law compliance*, *support given to vermicomposting by external organizations*, the *process simplicity* and the *willingness to innovate* as strong drivers. Adopters also indicated that their decisions were not driven by *economic incentives* or the *experiences of other successful adopters*. The rest of the factors evaluated presented a wide range of scores that on average could define them as drivers with "moderate" influence.

The group of **potential developers** is made up of two professionals from the wastewater treatment industry in Mexico. Although the information collected is not fully representative of the wastewater industry in Mexico, their answers to the questionnaire exhibit similarities in scores and justification to other respondents. They identify *lower capital and operational costs* and *policy and law compliance* as drivers with a very strong influence on the decision to adopt a new technology. They also identify *savings*, *process simplicity,* and *successful adoptions cases* as strong driving forces, giving special importance to the latter due to the lack of knowledge about vermicomposting within their professional field. These informants identify several factors as not influencing decision maker, *recommendations from external organizations* being the least important of all. The other factors identified as weak drivers are *creating a positive public image, innovation leadership* and *humus market price*, which contradict with the evaluation of potential and current adopters who identify the first two as strong or very strong drivers.

All the **potential adopters** considered in this study were municipal wastewater treatment plants in Mexico. According to their evaluation, *creating a positive public image* would be the strongest driver to adopt vermicomposting to stabilize their sewage sludge. Other less influencing, yet strong, drivers (in descending order of importance) are *avoiding landfill*, *savings*, and having the *support from external organizations*. The remaining suggested elements were also identified as drivers but with a moderate influence on their decision.

[4] The landfill benefits from the production of biogas from organic waste. In this case, the economic attractiveness found by other adopters becomes a constraint for the main business activity because the vermicomposting process is competing with the biogas production for the same raw material.

A summary of the scores provided by these groups is presented in Appendix 1.

4.1.1 Lower capital investment and/or operational cost

The treatment of sludge is the most expensive operation of the overall wastewater treatment system (Spearling and Andreoli 2005; pers. comm. Ramírez). Therefore, all the stakeholders share the opinion that lower capital investment and operational costs would make a technology more attractive than others would. Current developers and adopters affirm that vermicomposting is a cheaper treatment alternative, but the cost of the process depends on its design. It can range from "low-cost simple systems to high-investment complex designs" (pers. comm. Ashbee). Simple systems with low capital investment are usually favored, especially in developing countries. The characteristics and costs of different vermicomposting designs are compared in Appendix 2, based on the information provided by current adopters and developers. Although operational cost is usually low for any design, the capital investment can vary. In general, the cost of the treatment will increase as the method becomes more mechanized, more land is needed and a higher volume of waste is treated. It is impossible to determine an exact investment cost without considering the sum of all these factors. However, potential adopters may need to compare investment costs among the different alternatives in order to make a final decision.

4.1.2 Savings in energy requirements and waste disposal

All the stakeholders evaluated this factor as a driver, but its influence on the adopters is slightly lower than developers believe. Nevertheless, there is a general agreement that savings are very attractive and mainly related to reductions in energy requirements and waste disposal costs. Depending on the design characteristics and treatment scale, the process can be operated with no or very low energy requirement. Although energy savings have not been measured, current developers and adopters affirm that this is an energy efficient process (pers. comm. Ismail, Kale, Aranda, Romero, Carrera, Cardoso; *see* Appendix 2). "[Energy demand] could easily be met with wind or solar power" (Ashbee pers. comm.), which would be an advantage for communities not connected to the grid (pers. comm. Ramirez). Another source of savings is associated with the reduction in waste disposal costs: Vermicomposting diverts waste from landfill by transforming sewage sludge into a safe soil amendment that can be directly applied to the land. In addition, the process is usually simple and does not require the use of sophisticated equipment, which translates into savings because the need for expensive spare parts is eliminated. However, there is a competition between biogas reactors and vermicomposting systems for the same kind of waste. While landfills use organic wastes to produce biogas, vermicomposting produces organic fertilizers. The latter is a carbon neutral process, but eliminates the potential for producing energy from this waste.

4.1.3 Humus market price

Vermicomposting transforms organic waste into a nutrient rich organic fertilizer that could be commercialized (Edwards 2004). Returning an economic value to what once used to be a waste is very attractive, especially when the market price is high. Thus, this factor is evaluated as a strong driver by several stakeholders. However, some current and potential developers affirm that this driver can become a barrier. Wastewater treatment facilities should consider all the collateral commercialization and distribution problems that might be experienced due to the different nature of their main activities (pers. comm. Cardoso, and

Ramirez). The most experienced vermicomposting developers mention that several individuals and organizations have installed the treatment driven by the idea of commercializing the end product, but soon became disappointed and abandoned the operation (pers. comm. Aranda, Carrera, and Romero). Humus market price could be very appealing and strongly drive a greater adoption of this technology, "but this is the wrong reason to adopt the treatment" (pers. comm. Aranda). There is no formal market established for this product, or a standardized vermicomposting methodology. Therefore, different methods, with different wastes, under different market conditions, produce a wide variation in the humus market price. In Mexico, the price can be elevated in the northern arid regions where land degradation is a problem, while in some other parts of the country the price is not high (Rodríguez-Quiroz). According to Dr. Carrera, the market price for humus in Mexico can vary from 70 USD/ton (central and southern regions) to 1,500 USD/ton (north). In addition, González holds that the potential revenue from the worm castings cannot be compared with the income obtained from producing biogas. Developers sustain that adopters should give more importance to the humus ecological value than to its market price. As Dr. Aranda affirms, "should vermicomposting of sewage sludge be motivated by the humus price, the project will end up in a dramatic failure. There are no established distribution channels and consumers may not want a fertilizer produced from sewage sludge" (pers. comm. Aranda).

4.1.4 Economic incentives

On average, all stakeholders consider economic incentives a driver except current adopters who did not need them to install their worm farms. In addition, conflicting viewpoints were found within the group of current developers regarding the need for economic incentives (*see* Appendix 1). There is a general belief that incentives would only have a moderate effect on adoption of the technology. "It would help, but projects will not be stopped if incentives are not available" (pers. comm. Santos). "It is nice to have incentives, but the process should stand alone without incentives if it is to be a true success" (pers. comm. Ashbee). On the contrary, other developers giving a high evaluation to this factor affirm that municipalities would be highly motivated to adopt this treatment if economic incentives were in place. On this, municipalities support Santos' viewpoint and affirm that incentives are desirable, but the treatment would be adopted even if they were not available because they are legally obliged to give treatment to their sewage sludge (pers. comm. Félix, Rodriguez, Loaiza).

4.1.5 Innovation leadership

There are conflicting opinions about the influence of this factor. No consensus is found when marks are compared among regions or among informants. On average, developers (both current and potential) perceive that adopters are less driven by this factor than what adopters declare. In both groups of adopters, the desire to innovate was evaluated as a strong factor. Nevertheless, it is important to mention that adopters justify their scores by associating this factor with the creation of a good public image. "It is always very well seen that you do something for the environment", expressed one of the potential adopters. Therefore, they might not be evaluating the influence of their willingness to innovate *per se*, but reflecting on their desire to create a good public image. However, studies on factors driving innovation report that adopters are more susceptible to produce innovations than developers when they are not fully satisfied with their existing alternatives (Urban and von Hipper 1988, Braun 2007, Raasch et al 2008).

4.1.6 Create a good public image

The average distribution of scores presents a similar trend to that of the evaluation for *innovation leadership*. Potential and current developers perceive this factor as less influential than what adopters declare. For potential adopters, creating a positive image within their community would be the main reason that would drive them to adopt this technology. It is important to keep in mind that all the potential adopters participating in this study are municipalities. Therefore, their attitudes toward social needs and public opinion are justified. However, the different groups of stakeholders share the opinion that the holistic approach of vermicomposting creates a good impression in the community and "it is an extremely good publicity for a company" (pers. comm. Santos). People associate it with food security and pollution prevention (pers. comm. Grand). Therefore, this could be translated in a political context to more votes, or to lower social rejection towards activities that otherwise would be unpopular (e.g. the installation of a wastewater treatment plant in the vicinity). Current adopters confirm that their public image was significantly improved after the installation of the vermicomposting treatment.

"As a landfill, we needed to build this worm farm to reduce the community's lobby against our operations" (pers. comm. González, landfill representative).

"We have created a very positive image in our community and several groups of students are frequently visiting our facilities" (pers. comm. Haros).

"We receive visits all over the year. Local schools call us asking for vermicomposting workshops. Potential adopters also come and visit our facilities to learn about the process" (pers. comm. Delgado).

4.1.7 Avoid landfill

The idea of recycling sewage sludge and producing an excellent soil amendment is viewed as a positive and holistic approach to address waste management problems. However, informants present heterogeneous opinions on how influential the desire to avoid the use of landfills is. It is evaluated as a strong driver by the current developers and both groups of adopters, excluding the landfill site. Potential developers present conflicting opinions on this item. While Santos affirms that the current practices in Mexico do not stimulate landfill avoidance, Ramírez argues, "If the sludge could be used for agricultural applications, this would be a strong driver (pers. comm. Ramírez)".

4.1.8 Successful adoption cases

The existence of other successful adoption cases demonstrating the effectiveness of this technology is an important driver for everyone, except for early (current) adopters who were driven by the potential to innovate. Potential developers affirm that one of the main reasons that have prevented a greater diffusion of this technology is the lack of pilot scale projects demonstrating with tangible data the real potential that this technology can achieve (pers. comm. Santos). Successful case studies would positively influence other companies to adopt this treatment. "It would help to erase questions about its performance and costs" (pers. comm. Ramirez). Potential adopters support these viewpoints and add, "It may help to see how it works in a different facility, but it would not make me take the decision until I run a pilot test with my own waste. The characteristics of sewage sludge may be very different from one plant to the other" (pers. comm. Felix). Although current adopters understand the previously expressed opinions, they affirm that the lack of successful cases did not stop them from adopting this treatment. The latter can be explained by Dr. Aranda, who sustains that "(for innovators) there is nothing to lose if the treatment does not work. The worst thing that could happen is that the characteristics of the sludge will remain as they were at the beginning, but it cannot get worse than that" (pers. comm. Aranda).

4.1.9 Ease to obtain operators

The average evaluation of this factor indicates that this would be a driver for all the stakeholders, but with a lower influence than other identified drivers. Nevertheless, the evaluation was affected by the way in which the statement was formulated. "Ease of obtaining skilled/trained operators" was understood in two different ways: as the ease to find operators, or as the ease to train the operators. Therefore, the informants evaluated this factor considering one or both perspectives. In spite of this failure in the evaluation format, there was a general consensus from both approaches. Stakeholders consider that the ideal operators for this treatment shall be comfortable with those activities typical for farm labor. In a developing country, people with this profile are easy to obtain, but hard to keep. "There is a high turnover among operators in wastewater treatment plants due to low wages" (pers. comm. Ramirez). Nevertheless, training is not an issue. All the current developers agreed that training is easy and not expensive. "Everything the operator needs to know about the process can be learned in ten hours" (pers. comm. Carrera). The latter is an advantage over most of the conventional sludge treatment technologies that require sophisticated controls that shall be maintained by operators with minimum technical knowledge to guarantee their effectiveness. In conclusion, the provision of adequate operators for this treatment becomes a matter of selective recruitment based on skills and fair wages.

4.1.10 Support from external organizations

Although the decision to adopt this technology would not be based on a recommendation, it may have a moderate to strong influence. The study by Luken (2007) suggests that external influence on the decision to adopt a new technology would not be significant. This idea is supported by potential developers. However, this study has found that the average evaluation from both types of adopters suggests this factor as a potential driver with a strong influence. The latter is also supported by current developers, although their ranking indicates a lower level of influence. Nevertheless, the external influence identified by the informants in this study is limited to the scientific community, academia and government institutions. Research centers and academia are expected to present solid scientific evidence of proven performance, while government should officially authorize the adoption of this treatment. For municipalities, it is very important to get the scientific community involved. Moreover, most of the municipalities participating in this study affirmed that they would like to explore the possibility to adopt vermicomposting by running pilot tests in association with an external organization with a reputable scientific background. "I will not consider the opinion from an NGO, but if it the academia or any research center presented scientific and technical arguments, I would be willing to run a pilot test" (pers. comm. Félix). However, it is unclear how much external organizations may influence the decisions of a private company.

4.1.11 Process simplicity

The adoption of a process that is simple to operate is identified as a strong driver by all the stakeholders. "Wastewater treatment plants try to invest the least possible amount to stabilize sewage sludge because the conventional treatment is very expensive and complex. If the treatment did not require the use of sophisticated equipment, and yet were easy to operate, this would be a very strong driver for adopting this technology" (pers. comm. Ramírez). The simplicity of this method is one of its main attractions. However, some potential adopters are fully convinced that the process would not be as simple as presented for the volume of waste that they manage. As previously discussed, the complexity of vermicomposting depends on its design. Developing countries usually prefer to adopt simple systems in order to save in capital investment and operation costs, while generating jobs to their cheap and available labor force. However, when land or labor is scarce or expensive, the introduction of more sophisticated systems with mechanization becomes more reasonable. The latter viewpoint is confirmed by two vermicomposting developers. They explain that the complexity of the operation is directly proportional to the treatment scale because more equipment is needed for a greater volume of waste (pers. comm. Carrera). Therefore, the process is not simple anymore when managed as a large-scale process (pers. comm. Budzich).

4.1.12 Policy and law compliance

This factor is evaluated as a driver by all the stakeholders, with the lowest score given by the potential developers. All the informants shared the opinion that sewage sludge should be stabilized using an efficient system. They think that the installed treatment methods should make the sludge safe for humans and for the environment (if possible) above the legal standards. However, the general perception about regulations is characterized by origin. Informants in developed countries think that their regulations are very strict, while several informants in Mexico consider that their regulations are weakly enforced and that fines are needed for those that do not comply with them. Both current and potential adopters expressed that their willingness to comply with regulations is stronger than the law enforcement in the country. The latter is consistent with a previous study by Luken (2007). However, potential developers perceive that the current policy and law scheme would not stimulate potential adopters to adopt vermicomposting, while the latter affirms that regulations would be their main reason to install the treatment. Nevertheless, it is important to remember that in this study, the group of potential adopters only includes municipalities. The viewpoints from the private sector shall be considered to validate this position.

4.1.13 Additional drivers

Previous studies on technology innovation have underestimated the importance of environmentally sound technologies, which seems to be a new trend for the organizations participating in this study. Although it was not presented as a unanimous claim, several informants from all the stakeholder groups affirm that there is a recent need to find more economic alternatives and to produce reusable organic fertilizers from sewage sludge. Managers of wastewater treatment plants are starting to look towards the reuse of biosolids as soil amendments due to the current land degradation problems and the need to achieve reductions in waste disposal costs. However, there are health concerns and regulations that restrict the use of sewage sludge. Should higher pathogen reduction levels be achieved, this waste could be considered a reusable by-product with more applications and without health risks from direct contact with it. Thus, a niche opportunity is being created in the prevailing system for the diffusion of vermicomposting.

4.2 Barriers to adopting vermistabilization

There was a consensus among the different stakeholders to identify *uncertain costs*, *uncertain performance*, *controlling an unknown process* and *lack of economic incentives* as barriers in decreasing order of importance. However, there is a wide range of opinions for the remaining factors. Contrasting viewpoints are especially important for the factors related to *lack of information* and *higher labor and land demands*. The average scores seem to suggest that current developers and current adopters have a less negative position on these subjects as compared with potential developers and potential adopters. Therefore, it could be inferred that a deeper knowledge about the treatment might decrease some existing barriers grounded on perceptions.

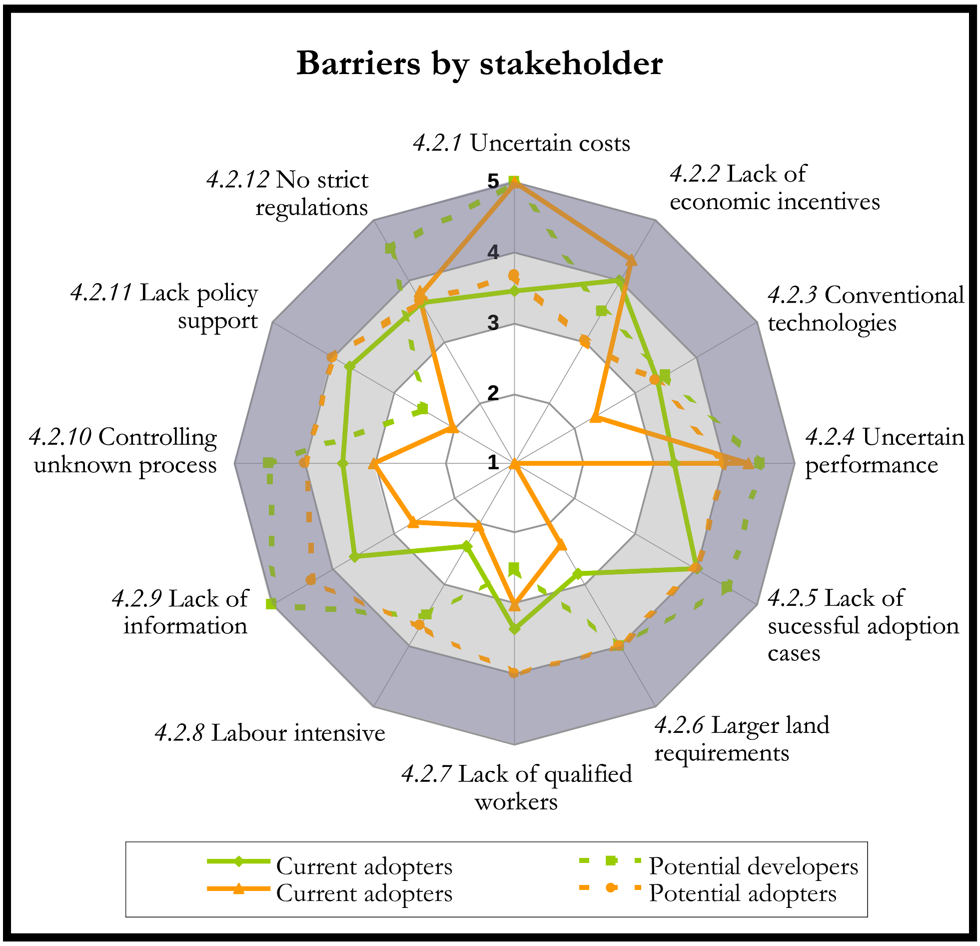

Figure 4-2 *Evaluation of barriers by stakeholder*

According to current adopters, the *uncertainty about the costs* of this treatment would act as the strongest barrier for potential adopters. These informants also recognized the *lack of economic incentives uncertain performance, lack of strict regulations, lack of qualified workers, controlling an unknown process* as other barriers but with a level of decreasing influence from strong to moderate. Their average scores also seem to indicate that *low cases of adoption cases*, *labor-intensive demands*, and the satisfaction with *performance of conventional technologies* would have no influence on the decision makers. The group presents conflicting viewpoints regarding the evaluation of the other factors suggested in the questionnaire.

The group of potential developers is highly concerned with the uncertainty produced by the lack of information about this treatment, especially about economic aspects. Other strong barriers this group identified are *uncertain performance*, *lack of successful cases* of implementation, reaction against *controlling an unknown process*, and the *lack of strict regulations*. In addition, there are conflicting viewpoints regarding the influence of *lack of qualified operators* and *lack of policy support*.

The strongest barriers potential adopters identified were (in descending order) the *lack of information*, *lack of qualified workers* and *controlling an unknown process*. Municipalities indicated that their decision to embrace a new treatment alternative is only moderately influenced by the *performance of the conventional treatment technologies* and the *lack of economic incentives*. The average evaluation for the remaining factors identifies them as strong barriers, but the individual scores indicate a wide range of positions.

A summary with the scores provided by stakeholder group is presented in Appendix 1.

4.2.1 Uncertain costs

There is a consensus among current informants that uncertainty about investment and operational costs would be a strong barrier. "[This is a] strong barrier because there are not sufficient facilities in place in order to understand this process" (pers. comm. Ashbee). Despite the fact that lack of verifiable cost information did not prevent the early adoption of this technology, current adopters also consider this a strong driver for potential adopters. According to Delgado, "the process is economic, but the initial question of all the potential adopters that visit our worm farm is always related to costs" (pers. Comm. Delgado). Potential adopters consider that cost is a factor that shall be analyzed with care before making the final decision in order to prevent false cost expectations and determine whether the investment will be recovered or not (pers. comm. Félix, Loaiza and Rodríguez). Municipalities shall be careful when analyzing costs for two reasons. First, the treatment of wastewater and sludge is still a low priority issue in Mexico (Bauefeld *et al* 2008, pers. comm. Cardoso and Ramirez); therefore, most WWTP operate with limited budget. Failures to anticipate the exact investment cost could eventually stop the project. Second, the lack of verifiable information has resulted in the emergence of some opportunist groups that present inflated prices, which creates the false impression that the treatment is more expensive than it really is (pers. comm. Rodriguez). Furthermore, the lack of information about costs can also impede the promotion of the technology at the policy level. Dr. Ismail affirms, "Policy makers expect to get statistics" in order to compare against the conventional treatments. However, as previously discussed in Section 4.1.1, the cost of a vermicomposting process depends on the design method. A cost comparison for several vermicomposting facilities is presented in Appendix 2 in order to provide the reader with an approximate of current costs. The average cost of vermicomposting is compared to conventional systems in Chapter 2, Table 2-2, for illustrative purposes.

4.2.2 Lack of economic incentives

The average evaluation from stakeholders suggests that the lack of economic incentives could be a barrier with a moderate to strong influence on the decision to adopt vermicomposting. Current adopters give a high importance to this element. Although they did not benefit from any incentive to install their treatment, they consider that this factor would have a high influence on potential adopters. “Potential adopters visiting our facility are very concerned about costs” (pers. comm. Delgado). The evaluation from potential adopters suggests the opposite. Their scores indicate that this factor has a moderate influence on their decision and they are the group less influenced by this barrier when compared with the other stakeholders. For them, economic incentives are important, but their absence will not stop them from installing the system should it be necessary to comply with the regulations (pers. comm. Arada, Félix, Loaiza and Rodríguez). However, it is important to remember that the group of potential adopters in this research is made up of municipal wastewater treatment plants. Therefore, this evaluation shall be complemented with the opinion from private organizations. On the other hand, there is a debate among developers regarding the influence of this factor. Those that affirm it would be a strong barrier explain that the lack of incentives would discourage the adoption of this technology and slow down the pilot testing stage (pers. comm. Aranda, Carrera, Ramírez and Rodríguez). Incentives are also needed because “grants do help to offset high capital costs (of mechanized operations)” (pers. comm. Budzich). In contrast, some developers explain that the low economic support provided by policy makers is the result of lack of information (pers. comm. Cardoso). These viewpoints are based on the understanding of economic incentives as instruments administrated by the government. However, Santos argues that *savings* could be considered as sufficient incentives *per se*. “If grants are not provided, but significant cost reductions can be achieved, potential users would still adopt it” (pers. comm. Santos).

4.2.3 Satisfaction with conventional technologies

With the exception of current adopters, this factor is evaluated as a moderate barrier by all stakeholders. There is a debate among the informants on how much the dependency on conventional and proven technologies may affect the introduction of vermicomposting as an alternative treatment. Several previous studies suggest that there is an inertia among organizations that locks them into conventional technologies (Arthur 1989, Aylward 2006, Hannan et al 2004, Genschel 1997). Foxton and Pearson (2006) allege that this technology lock-in creates barriers for more sustainable innovations. Once a technology has proven effective, users will refuse to adopt a new alternative (Pierson 2000). However, other sources indicate that there are embedded problems in the design of conventional technologies since they are only effective under specific climatic, sociocultural, political and financial conditions (Bauerfeld et al 2008). Therefore, current adopters argue that the initial inertia of the system would not be a strong barrier because conventional technologies have not been fully satisfactory. Indeed, Haros explains that his organization was motivated to adopt vermicomposting due to the problems with conventional treatments, the lack of other effective and environmentally sound technologies in the market, and their desire to give a further use to their waste (pers. comm. Haros). Thus, current adopters infer that conventional treatments are probably favored due to the lack of information about vermicomposting. In contrast, potential developers explain that the decision to adopt this new technology is a matter of a cost-benefit analysis. Furthermore, they argue that current systems present limitations but are proven technologies, whereas little is known about vermicomposting. To this discussion, the potential adopters add that it would be hard to introduce vermicomposting as a new treatment when the facility has already adopted a different system (pers. comm. Rodríguez), but "we would be interested in exploring this new option for smaller treatment facilities that are yet to be installed" (pers. comm. Loaiza). Therefore, with the exception of one municipality, all the potential adopters affirm that they would consider vermicomposting as a treatment alternative in the future and would like to run small-scale pilot tests to verify the adequacy of vermicomposting under the characteristics of their operation (pers. comm. Anduaga, Félix, Hernández, Loaiza, and Rodríguez).

4.2.4 Uncertain performance

The average evaluation indicates a consensus among stakeholders that identifies this factor as a strong barrier. Potential developers assume that potential adopters would prefer to see an installed vermicomposting process in operation with a satisfying performance before adopting the technology. "Managers may want to avoid any risks related with a bad operational performance that might create problems with regulatory compliance" (pers. comm. Ramírez). However, there are very few projects of that kind and most of the information being reported is related to studies that are focused on academic research at the laboratory scale (pers. comm. Kale). Current adopters agree on this viewpoint. For them, this barrier results from the lack of information. They consider that ignorance about vermicomposting has restricted a greater adoption of the treatment because it is still unknown by most organizations (pers. comm. Haros). Moreover, even those that have read about the topic do not fully understand its potential because they need to observe and get involved in the operation in order to understand the system (pers. comm. Delgado). On that perspective, current developers argue that only companies expecting to obtain an economic benefit from this treatment will find an uncertain performance as a barrier. For those driven by the desire to produce an environmental benefit, the fear towards failure would be lower (pers. comm. Aranda and Carrera). Nevertheless, for one of the potential informants participating in this study, the performance of vermicomposting is not under question. He claims to be convinced that vermicomposting is an excellent treatment alternative to produce excellent quality biosolids but "the results do not justify the investment in a cost-benefit analysis. The investment in the current technology would be lost, it is hard to obtain land to install this treatment, more operators would have to be hired and the benefits would be low because the end product would not receive a further use".

4.2.5 Lack of successful adoption cases

This factor is evaluated as a strong barrier by all the stakeholders, with the exception of current adopters. This element is closely related to cost and performance uncertainty. Potential adopters consider that this element is one of the main barriers because there are many questions about the treatment. For instance, there is a concern about how to control the excess of worms or if the process produces smells (pers. comm. Loaiza and Rodríguez). Their viewpoint is also reinforced by potential developers. They affirm that the lack of successful adoption case studies creates several uncertainties about the final disposal of the end product, operational controls (e.g. what to do with excess of worms), costs and performance (pers. comm. Ramírez). For these groups, the wider diffusion of the technology relies on pilot testing and full implementation experiences that prove adequate performance over a couple of years. Although current developers also agree that the lack of successful implementation cases can be a barrier, they prefer to center their discussion on the reasons that may have slowed the adoption cases down. These reasons include low willingness to innovate, poor communication of existing projects, and lack of promotion within the wastewater industry (pers. comm. Aranda, Ashbee and Kale). Budzich, who develops a mechanized operation, also affirms that the current vermicomposting design needs to become more effective and efficient in order to become supported. In contrast, based on the evaluation and viewpoints from the current adopters, it seems that the lack of successful cases did not prevent the adoption of this technology about the group. One of the informants report to have learned from research, while other learned from direct observation of the system for other wastes, but they both decided to innovate on the sewage sludge treatment (pers. comm. Delgado and Haros).

4.2.6 Larger land requirements

There is a debate on the influence of this element. The average scores indicate that land requirements are not considered as a barrier by current developers and adopters, while potential developers and adopters consider this element as an obstacle with strong influence on their decisions. This trend may suggest that perceptions are affected by the level of knowledge about the treatment. Potential adopters and developers share the opinion that the process land requirements may be larger than the current space availability. This would impede the development of the project in densely populated areas where the cost of land is high. Wastewater treatment facilities are usually installed with limited free space that might restrict the on-site implementation of the project (pers. comm. Loaiza, Padilla and Ramírez). On the contrary, the viewpoints from current developers and adopters present a variety of opinions. Despite their average evaluation, some current developers support the viewpoint about larger land requirements, while others affirm that this factor may work as a barrier due to false impressions and inaccurate information about the treatment. According to the latter position, the paradigm about larger land requirements is true for the extensive vermicomposting designs. However, efficient designs based on intensive vermicomposting processes are less land demanding (pers. comm. Aranda, Carrera, Rodríguez and Romero). Nevertheless, viewpoints from current developers suggest that the vermicomposting facility may indeed require more space than the most popular conventional treatments. However, they affirm that provided land is cheap an available, this would not be a significant barrier in developing countries (pers. comm. Aranda).

The debate about how much land is required is an issue that needs clarification based on qualitative data. Since there is not a standardized design method, land requirements per unit of treated waste may vary among similar systems. Appendix 3 presents a table with land requirements from different currently installed treatments. The figures shall be used for illustration purposes only, as the real land requirements may be different from case to case. However, for the purpose of this study, these numbers become important for comparison among different technologies. For instance, a medium size vermicomposting process may present land requirements ranging from 0.22 to 5.9 hectares (2,200 sqm to 59,000 sqm), while the space needed for the installation of an aerobic digester would not exceed 2,000 sqm [5]. In order to put these figures in perspective, we can compare these land requirements

[5] The aerobic digestion treatment is commonly adopted by small and medium size wastewater treatment facilities. It may achieve adequate reduction in the organic matter concentration. However, it does not achieve high disinfection levels. Should disinfection of sewage sludge be a treatment objective, an additional disinfection operation shall be considered.

with their footprint for agriculture. In Mexico, a small farmer owns 9-10 hectares (pers. comm. Velázquez, chief officer of the Agriculture Development Office, SAGARPA Sinaloa). Therefore, the installation of a vermicomposting facility for a medium size wastewater treatment facility would be equivalent to less than the productive area of one small farmer. However, whether the land requirements are excessive or not depends on how much land is available for this operation near the WWTP. Further estimations on land requirements are shown in Appendix 4 for low, medium and high footprint scenarios in small, medium and large facilities.

4.2.7 Lack of qualified operators

There is not a consensus among stakeholders regarding the influence of this factor. While potential adopters consider that higher labor requirements would be a strong barrier, current adopters and developers provide a moderate average score and potential developers consider that this would not be an obstacle. Regardless their average evaluation, potential adopters present conflicting opinions on this issue. On one side, Santos considers that the lack of trained operators would not impede the adoption of the treatment because it may be simpler than the technical knowledge required for the other conventional treatments. On the other side, Ramírez holds that the high turnover at the operator level will require a constant training expenditure. The perceptions from potential adopters support the position adopted by Ramírez. Nevertheless, it is not clear from the information provided by the potential adopters how much this factor may affect their decision about vermicomposting as this latter viewpoint would also be true for the other treatment types. For current adopters the problem is only centered on the difficulties to find operators with a characteristic profile that would be willing to work and learn from this process. Some current adopters support this argument and declare that "this is the fact that is interfering with the (success of the) project" (pers. comm. Kale). They explain that training is easy and economic, but it requires a different type of operator. Moreover, other current developers affirm that the discussion shall be a matter of concern not at the operator, but at the technical and designer levels. The lack of experts in this field may act as a limiting factor for the greater adoption of this treatment (pers. comm. Holcombe and Romero).

4.2.8 Labor intensive operation

The evaluation of this element present clearly divided positions among stakeholders. Potential developers and adopters consider that the treatment would require an undesirable increase in their labor force. However, most current developers and adopters perceive an increase in labor force as an opportunity to create employment in developing countries, which could be reduced through mechanization.

Box 4-1 Analysis of labor requirements for a medium size facility

Analysis of labor requirements for a medium size facility.

The most common disinfection treatments are alkaline stabilization and solar drying. Therefore, the figure considering the land requirements for the conventional alternatives shall be modified to include the land requirement that corresponds to the space for alkaline stabilization or solar drying. While the former could be installed in a space equivalent to the aerobic digestion, the latter will also demand extensive land requirements.

According to Romero (pers. comm.), non-mechanized intensive vermicomposting requires the input of one operator every 500 m^2. Thus, a medium size facility would require a minimum workforce of five operators. On average, the complete management of a medium-size wastewater treatment facility demands 12 employees (pers. comm. Padilla). Therefore, the previous figure represents almost a 50% increase in the current workforce.

4.2.9 Lack of information about vermicomposting

The average evaluations from stakeholders are consistent with the theories of technology and innovation adoption. This research found that current (early) vermicomposting adopters and developers were not stopped by the lack of information about this treatment. For them, the information from early research and implementation stages was sufficient to develop their own vermicomposting system (pers. comm. Delgado, González and Haros). To current developers, the existing information is enough to illustrate others on how to develop the system, but it has been poorly communicated (pers. comm. Aranda, Rodríguez-Quiroz and Romero).

The lack of information slows down the technology diffusion process, but it cannot be translated as a lack of interest in this technology. According to Aranda, municipalities are usually interested in receiving more information about this technology when they are informed about its existence. Nevertheless, Kale affirms that once the information about vermicomposting is communicated, certain reluctance is maintained towards the adoption of this new technology. Spreading information about the characteristics and advantages of vermicomposting will not immediately stimulate a greater adoption of the treatment. For potential adopters and developers, more information is needed regarding costs and operational control parameters. These factors may not be very important for them during an initial screening, but uncertainty on this issue could stop the project by the time of taking a decision. For municipal wastewater facilities, their main concern relies on the performance side. Most municipalities affirmed to have a previous basic knowledge about vermicomposting and expressed their interest in running pilot projects before the adoption. Up to date, only small-size facilities have ventured to evaluate the efficiency of the vermicomposting treatment under their local conditions (Cardoso et al 2008), while medium and large-size works present a more conservative position.

4.2.10 Controlling an unknown process

On average, general agreement indicates that this factor is a barrier. However, there seems to be a discussion among the informants from the groups of current developers and current adopters about the influence of this element. On the contrary, the informants from the potential developers and potential adopters are more consistent in their positions. Although some current developers affirm that control is not an issue, Budzich claims that the process can be easily operated at small scale, but controls are still under development for large scale. Rodríguez-Quiroz and Ashbee emphasize the importance of establishing standardized control parameters. According to them, an organism should be created in order to verify the correct performance of the treatment and adequate quality of the end product (pers. comm. Ashbee and Rodríguez-Quiroz). On the other hand, some current adopters consider that the simplicity of this treatment facilitates its control as compared with other alternatives that require a more sophisticated operation (pers. comm. Delgado). However, González argues that despite its simplicity, the challenge of verification and correct control of the process parameters should not be underestimated. The lack of an adequate control could kill a significant proportion of the worm population (pers. comm. González). This latter viewpoint seems to be the main concern among potential adopters and potential developers who express their concern about their lack of knowledge regarding the proper management of the worms (pers. comm. Loaiza, Ramírez, Santos). In sum, the lack of information about the operational control parameters may produce an initial rejection. Albeit simple, the process requires constant monitoring of the operational variables. Chapter 2 describes the most important process controls that shall be observed in order to prevent operational problems and achieve the desired performance.

4.2.11 Lack of policy support

The influence of this element is unclear. It seen as a barrier by potential adopters and current developers, whereas potential developers and current adopters say the opposite. For current developers, the lack of policy support favors the development of conventional treatments. Potential adopters consider that vermicomposting should be within the list technologies recommended in NOM-004-SEMARNAT-2002 in order to increase the interest on this technology. On the other hand, potential developers and current adopters consider that the managers of the wastewater treatment plants would seek for an authorized and strongly supported treatment alternative in order to prevent problems during the implementation and operation stages. Thus, they conclude that policy level suggestions would not have as much impact as strict regulations.

4.2.12 Lack of strict regulations

According to the viewpoints gathered from the informants, regulations should be well enforced and support the adoption of a treatment method for sewage sludge. Based on the evaluation by all stakeholders, this factor is a barrier with a moderate-strong influence on decision makers. The informants consider that the lack of current support to the treatment results from the lack of knowledge about this technology among policy makers. More successful case studies are needed to demonstrate the efficiency and effectiveness of the treatment would help to gain political support. However, the influence of regulations is limited by the level of law enforcement that each country can achieve. The Mexican sewage sludge regulation (NOM-004-SEMARNAT-2002) is not well enforced and does not consider sanctions. This results in lack of motivation to provide an effective treatment to their waste.

4.2.13 Additional barriers identified by the informants

In addition to the previously identified barriers, the informants participating in this survey have suggested some factors that also may impede the adoption of vermicomposting. The questionnaire did not consider additional space to evaluate their level of influence; therefore, these elements are only generally described as follows.

- ***Operational logistics***. Although this new system does not require significant inputs of energy or chemicals, the use of a bulking agent is necessary to achieve a specific porosity in the material that would allow the movement of the worms through it. This creates a barrier regarding the logistics of the operation for three reasons. First, enough bulking material shall be provided, which would be an operational limitation if it is not available. Second, the mixture of the bulking agent and sludge to guarantee an adequate feedstock to the worms can be complicated to manage at large volumes. Lastly, as one of the main advertised advantages about this treatment is the possibility of producing an excellent organic fertilizer, its further use becomes important. The lack of distribution channels for this end product may be a barrier as it produces the impression that several resources are being invested to obtain no benefits.

- ***"Waste-to-energy" paradigm***. The recognition of global warming and climate change as a major environmental problem has been become a topic of high political implications and a priority in the global agenda. The current scheme of economic incentives strongly supports the installation of projects to produce renewable energy from organic waste in order to decrease the emissions of GHG. Since vermicomposting is an aerobic degradation, it is not possible to recover methane to produce electricity. Potential adopters affirm that anaerobic digestion is their preferred treatment option for sewage sludge because it allows the recovery of biogas. Under the existing energy paradigms of the current system, this discourages the adoption of vermicomposting in a cost-benefit analysis. It would be hard to compete against the newly created "waste-to-energy" industry that is interested in benefiting from green certificates and CDM projects, unless similar incentives and political support were offered for vermicomposting projects.

- ***Sewage sludge characterization.*** Several studies report the earthworm potential to remove heavy metals and other toxic constituents from organic matter (Tharakan et al 2006). Bioremediation practices consider their use to enhance the quality of soils (Edwards, 2004). However, as described in Chapter 2, they are not immune to the presence of these materials. Although the characteristics of sewage sludge from domestic discharges are not toxic to the worms, the introduction of industrial discharges in the influent might affect their reproduction rate and even present a risk to their survival (Ma 1983, Ma 1984, Neuhauser et al. 1984, Reinecke et al 1996, Spurgeon et al. 1994). For instance, it is known that the sludge from the food and beverage industries have proven to be toxic for the worms (Singh et al 2010, pers. comm. Carrera).

- ***Influence of current wastewater treatment designers.*** The importance of current designers should not be underestimated. The study by Braun (2007) suggests that they could act as a barrier against the introduction of innovative solutions. Generally, there is little participation from the adopters on the decisions regarding this operation. Therefore, the decision upon the type of treatment installed for sewage sludge relies on the designer of the WWTP. Current designers in the wastewater treatment industry are usually engineers that do not have a background in biology. Informants from the current wastewater industry manifest their concerns about the use of a living organism that results unfamiliar to them and would not know how to control.

- ***Lack of communication channels.*** Communication is an important barrier. The information about this technology has not been efficiently communicated to policy makers, professionals in the wastewater industry and potential adopters. More successful adoption cases are needed together with quantitative data regarding costs and potential energy savings. Promotion in commercial exhibitions and conferences organized by some groups of farmers has helped to spread the technology in the agricultural sector (pers. comm. Velazco), but a similar strategy has not been adopted in the water industry yet.

4.3 Perceived potential for the adoption of vermistabilization

Despite the drivers and barriers presented above, the viewpoints from stakeholders indicate that there is potential for a greater adoption of vermistabilization as an alternative treatment for sewage sludge. According to the information gathered from the questionnaire format (*see* Appendix 1), the stakeholders perceive that vermicomposting could be a viable treatment alternative depending on certain economical and technical circumstances described as follows.

4.3.1 Developed *vs.* developing countries

In general, all informants agreed that developing countries have the greatest potential to embrace vermicomposting, as they would benefit the most from this treatment. Although some potential is also perceived for developed countries, informants believe it would be limited by the eventual competition with conventional alternatives.

There is a generalized confidence from all the informants regarding the potential to develop vermicomposting in developing countries for several reasons. According to the informants, the technology has a high potential to be adopted because it is a low cost technology that would help to meet sanitation targets, decrease the dependency on imported organic fertilizers, and create employment. "These countries need cheap systems that can be easily controlled and operated in order to meet the sanitation goals", says Ramirez. Vermicomposting is a technology that can help to solve the problems associated with waste management and sanitation (pers. comm. Haros, Holcombe, and Kale). "It could be easily adopted because it is an effective and low cost technology" (pers. comm. Ashbee). In addition, not only the end product is pathogen safe, but also a nutrient rich fertilizer that would help to reduce the dependency on imported synthetic fertilizers (pers. comm. Grand, and Holcombe). "All this advantages make it an ideal treatment already, especially because it is cheap. Furthermore, it has the potential to produce employment" (pers. comm. Aranda).

Informants from developed countries are positive about the potential to develop vermicomposting at a greater scale in this region. They trust that the benefits would overcome the present obstacles and position vermicomposting in the market for conventional technologies. According to Holcombe, "there is not a better technology for sewage sludge. The conventional treatments produce sludge that here in the US could only be spread on the land". "It would be attractive if we could stabilize the waste in a sustainable way to produce an organic fertilizer", says Grand, a vermicomposter and designer from Austria. However, this opinion is not shared by their counterparts from developing countries, who are skeptical about this potential. They argue that developed countries would not risk in new treatments because "they have all the necessary economic resources to adopt already proven technologies" (Aranda, Ramirez and Santos, from Mexico). Nevertheless, they recognize that a high environmental awareness could change current paradigms. According to Santos, "Vermicomposting would only have potential in developed countries if they were driven by a high environmental awareness. This would be more likely to happen in Europe than in the US". Apart from sustainability factors, there are operational conditions that shall be considered. "It has potential in the US, but we need to refine the operational controls to make it suitable for large scale. Currently, only small-scale projects could be developed. The mechanized system is being tested. It has a good performance, but costs are higher than conventional technologies" (pers. comm. Budzich, from US). To that, Aranda affirms, "it is expected that expensive land and labor costs would attract developing economies to mechanized operations. However, they should keep in mind that the higher energy requirements might produce a negative energy balance and increase the operational costs. Low operational cost is one of the main advertised advantages of this technology" (pers. comm. Aranda).

4.3.2 Private *vs.* public WWTP

There are two key issues that differentiate the operation of a private and public WWTP: influent characteristics and budget. Mexican regulations stipulate discharge fines to wastewater parameters that do not meet the allowable limits for wastewater discharges. Therefore, it is common practice that industrial discharges are treated on-site and that municipal WWTP operate without significant industrial disturbances. Under this scheme, any disturbance can be easily detected and controlled so the sludge is safe for the worms (pers. comm. Ortiz). However, this condition may be hard to meet in an industrial facility that combines both types of discharges, increasing the possibility that sludge characteristics may not be processed by the worms. On the other hand, private companies operate motivated by revenue, while the objective of municipalities is to produce social benefits and stick to a limited budget. In that sense, private companies might have the money to invest, but not a reason to do it, whereas municipal works might have the interest to adopt vermicomposting, but not the economic resources due to their limited budget. Nevertheless, according to Cruz, "private plants could become the easiest adopter of this technology". In Mexico, private small-scale wastewater treatment plants for domestic and industrial discharges are common within private companies (CONAGUA 2010). Many of these companies do not comply with the waste management regulations because of the poor law enforcement in the country (pers. comm. Haros) and the high cost of conventional treatments (pers. comm. Cardoso). "They need cheaper and less sophisticated alternatives" (pers. comm. Ramirez). Vermicomposting is a low cost method that "is attractive for a company because they are always looking for savings to obtain the highest profit" (pers. comm. Holcombe). If enough space were available, private companies would be seduced by the possibility of saving in waste disposal using a technology that cheap and easy to operate due to their low volume of sewage sludge (pers. comm. Ramirez and Santos). In addition, the adoption of this treatment would significantly favor the company's public image, which can be transformed in to good publicity (pers. comm. Santos).

4.3.3 Small *vs*. large scale

While small-scale implementation is seen as feasible, there is a discussion whether large-scale projects could successfully be developed. Budzich affirms that the waste characteristics and volume should be analyzed at all sites prior to determine if vermicomposting is a suitable project. There is the potential to adapt the system in order to accommodate larger loads, but operational controls become more complex as the volume of waste increases. The current vermicomposting technology might require too much land for a large-scale project.

Currently, small municipal wastewater treatment plants present a situation similar to that of private wastewater treatment plants. They have problems adopting an efficient treatment for sewage sludge because of the high capital investment and operational costs of the conventional technologies (pers. comm. Ramirez). Vermicomposting can be very attractive because it is economic (pers. comm. Cardoso, Grand, and Holcombe). Their small production of sludge make the treatment easily controlled and with a low risk of operational failures (pers. comm. Cardoso, Kale, Loaiza, and Rodriguez). However, the implementation depends on the budget assigned to the municipality. Some do not have budget to pay for operators and have problems with a high turnover among employees, which would increase training requirements (pers. comm. Santos).

Whether a medium-large scale vermicomposting project could be developed for sewage sludge is a matter of debate. Experience shows that large-scale pilot projects have failed in the past (Edwards 2004). Nevertheless, some vermicomposting developers are confident that the flexibility of the treatment design allows an operation at any scale; its potential for success depends on having enough land and feedstock available. However, despite the confidence on its implementation, there is another group of developers that question the feasibility of a large-scale operation. The questions are grounded on the belief that land requirements may be too large (pers. comm. Kale, and Ramirez) and operational controls hard to maintain at large loads (pers. comm. Budzich, and Kale). In that sense, it would be difficult to install a large-scale project in highly populated areas, or with high agricultural value (pers. com. Cruz, and Velazco). Moreover, up to date, there are not demonstrated large-scale projects. "We need to prove its suitability to large scale before adopting it", says Loaiza. Grand affirms that the new continuous flow technologies would allow a large-scale implementation (pers. comm. Grand). However, Budzich sustains the opposite. After operating a large-scale system for a municipality in Philadelphia, he affirms that the process is "not operational at large scale yet. It is still hard to control the system. It has potential, but we need to refine the system's physical, chemical and biological control parameters.

This study contacted twelve municipal wastewater treatment works with different treatment capacities to determine their interest in vermicomposting. The interviews indicate that only facilities with medium-high budgets and treatment capacity up to 75 liters per second would be currently interested in this technology. The treatment plants using vermicomposting at a trial stage are facilities operating aerobic treatments with high costs that have an agreement with a research or academic institution in order to demonstrate the benefits of the technology. Some other facilities are interested in running a trial test. Those are mainly facilities with aerobic or anaerobic treatments that operate with high costs and present problems with odor control. They are interested in disinfecting the sludge to use it as a safe soil amendment. In some cases, these facilities are also considering a future expansion of their current capacity and are interested in adopting treatment alternatives that are more sustainable than conventional practices. The treatment plants that remain skeptical are those using solar drying, a method that is cheaper and equally effective in stabilizing the sludge than vermicomposting. They would only adopt this treatment if vermicomposting demonstrates attractive advantages over solar drying. Finally, those plants that would not consider vermicomposting as a treatment method are the facilities with no intentions or possibilities to give a further use to the sludge.

5 Adopting and diffusing vermicomposting

This Chapter describes the current situation of the adoption of vermicomposting in Mexico and the elements that are needed to diffuse this technology as a new treatment option for sewage sludge. Section 5.1 introduces the structure followed to analyze the information in this chapter. Section 5.2 presents a list of 41 elements identified by this research as part of a successful vermicomposting system. The current and ideal states of these elements are described based on the viewpoints gathered from the stakeholders and supported by literature review when necessary. Section 5.3 evaluates the maturity of the current system based on the previous comparison. Finally, Section 5.4 concludes with a discussion about the current potential for adopting vermicomposting in sewage sludge.

5.1 Introduction

The process of an integral sewage sludge management can be divided in three general stages: sludge production, sludge treatment and sludge disposal. Figure 5-1 presents a flow diagram that illustrates these stages considering vermicomposting as the chosen treatment alternative. The system starts with the wastewater discharge from domestic and industrial users. While there is one discharge from domestic users that goes directly to municipal sewage works, industrial users can have domestic and industrial discharges. Ideally, these two different waste streams would be separated to provide a wastewater treatment according to the characteristics of their pollutants. Industrial users may have their own treatment facility or use municipal works for the treatment of the domestic discharge. Should industrial and domestic wastewater be managed by different sewer systems, the biological wastewater treatment plants will produce sludge with domestic characteristics. The high pathogen content of this sludge requires a further stabilization treatment. In this system, the sludge undergoes an on/off-site vermistabilization process with a bed design, similar to that described in Chapter 2, Section 2.3.3. A previous feedstock and bed preparation step is need before the treatment process. Once the waste is stabilized, the worm humus passes through the typical management operations. Lastly, the humus produced is transported to its final destination for disposal or further use. For the purpose of this study, these stages can be additionally defined as follows:

Sludge production: it involves all the activities that occur prior to the treatment process and all the decisions taken before the treatment facility is installed (including its conceptual design).

Sludge treatment: it involves the activities and decisions related to the installation and operation of the vermicomposting facility.

Sludge disposal: it involves all the activities and decisions that occur once the sludge is stable.

The information presented in this chapter was obtained from the semi-structured questionnaire and semi-structured interviews described in Chapter 1. Stakeholder viewpoints were gathered from 19 semi-structure questionnaires plus 13 hours and 40 minutes of semi-structured interviews via phone conference. The information obtained from the data gathering process corresponds to a variety of topics that have to be classified in order to allow a better management of the information. Thus, the data is separated into four factors described as follows:

Economic factors: Factors associated with economic indicators such as costs, revenue, cash flow, economic incentives, and position before competitors.

Management factors: Factors associated with the implementation of a long-term operation, resource allocation, management system, transparency, information networks, marketing and logistics.

Political factors: Factors associated with the position and support from government institutions and policy makers, political affairs, institutional framework, policies, and regulations.

Technical factors: Factors associated with the technology implementation, treatment operation and quality of the end product.

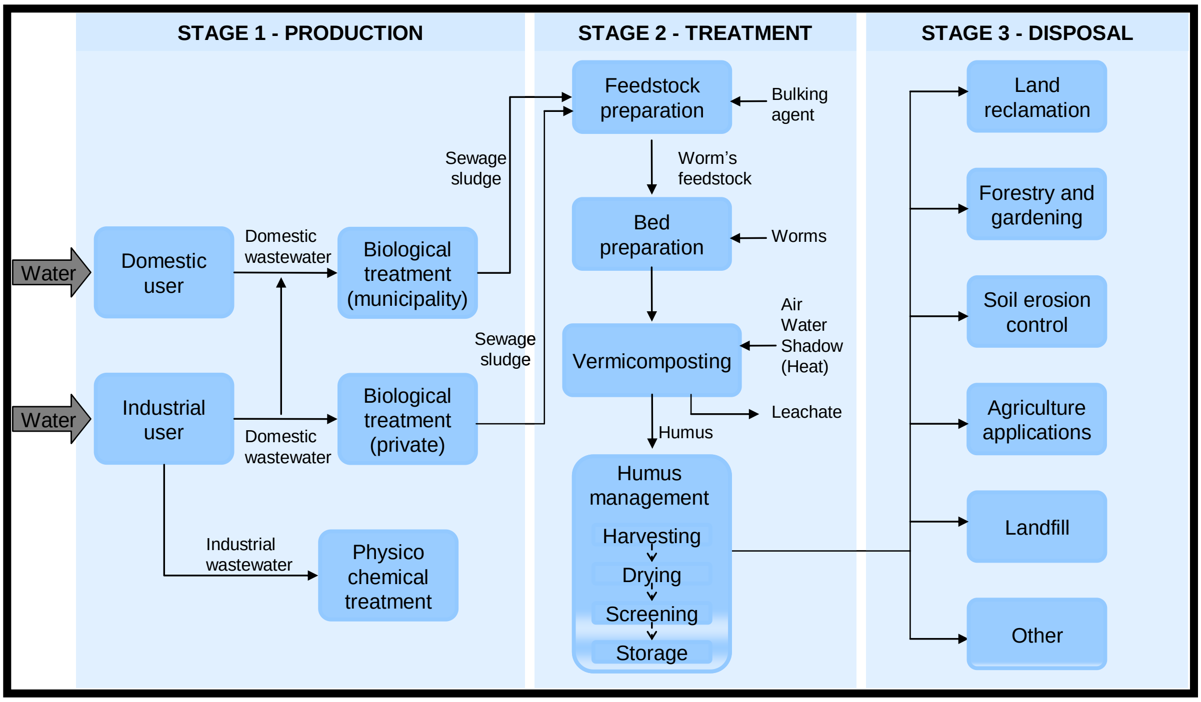

Figure 5-1 *Stages of the vermicomposting process for the recycling of sewage sludge*

5.2 Main elements for a successful adoption and diffusion

The adoption of vermicomposting is a decision that should consider several important elements in order to guarantee the successful implementation and long-term survival of this treatment. This research identified 41 key elements based on the viewpoints expressed from the stakeholders and the supporting literature review. This section discusses these elements by comparing their perceived ideal and current situation.

5.2.1 Sewage sludge production

5.2.1.1 Management factors

Sludge production records: Ideally, every wastewater treatment facility should maintain a record of their sludge production. This information is necessary to design an adequate treatment facility and it could be used as a baseline to plan future expansions. Besides, the sludge production records could facilitate the identification and quantification of seasonal peaks and would be useful to detect abnormal behavior in sludge production. In general, there is a lack of control regarding sewage sludge production, treatment and disposal. Current estimations indicate that 640 million dry tonnes per year of sludge are produced in the sewage works (LeBlanc, 2008). However, this number may not represent the real condition since most of the facilities do not keep a record of their sludge production (Cruz-Ojeda pers. comm.) despite it being a legal requirement established in NOM-004-SEMARNAT-2002. Government agencies justify this poor law enforcement by explaining that they operate under limited human resources, which restricts their capacity to monitor the compliance to the law (Cruz-Ojeda pers. comm.).

Communication channels

Effective flow of information among key process actors is important. Communication channel among informants should help to identify common needs and solutions. In addition, this information should be adequate and sufficient to allow decision makers consider vermicomposting among their treatment option. In practice, communication channels are poorly established. Although research on vermicomposting has been done since the 1980s (Aranda pers. comm.), little is known yet by the potential adopters. Communication problems are especially significant among institutions. While CONACYT supports public and private investment in innovation, most of the informants were not informed about these grants. On the other hand, the lack of communication has not allowed an inter-institutional discussion to solve common needs. For instance, municipalities and CONAGUA are interested in treating sewage sludge in order to turn this waste into a useful product. This could produce a valuable organic fertilizer. However, some municipalities this would not be a strong incentive if they cannot give a further use to the fertilizer (Padilla pers. comm.). At the same time, organic farmers are demanding a greater support to organic fertilizers in order to compete with other organic producers in the global market (Torres pers. comm.). Although SAGARPA tries to attend this demand, they do not have enough information to provide a solution.

5.2.1.2 Economic factors

Economic incentives to produce non-toxic sludge: The sludge produced from the wastewater treatment operation must be non toxic for the earthworm (*see* Chapter 2, Section 2.3.2). The exposure of the worm to highly toxic sewage sludge has been one of the reasons behind the failed vermistabilization attempts in the past (Edwards, 2004). Policies instruments and regulations are not enough to promote an specific behavior (Elnaboulsi Jihad C, 2009). Therefore, economic incentives shall be given to support the production of a suitable sludge for vermicomposting. The Mexican Law of Federal Rights establishes discharge fees to wastewater pollutants exceeding the maximum allowance limits set in NOM-001-SEMARNAT-1996. These economic instruments have been created in order to encourage the separation of industrial wastewater from domestic discharges (Cruz-Ojeda pers. comm.). Despite its initial success, the performance of this instrument has been questioned (Ugalde, 2008).

Economic incentives to adopt vermicomposting: Economic instruments shall be utilized to incentive the adoption of a stabilization treatment in order to allow a safe further use of sewage sludge. In addition to these incentives, current developers consider that grants would be useful to reduce the high capital investment cost of mechanized operations (Budzich pers. comm.) and to break the "waste-to-energy" paradigm (Holcombe pers. comm.).

Investment cost: The treatment of sludge is expensive and the current regulations do not establish sanctions or incentives for the treatment of this waste. There are some economic incentives to support innovations, but they are not specifically designed to support this technology (Rivera pers. comm.). Grants and tax reductions for research, development, and pilot testing are provided under a limited budget by CONACYT (Rivera pers. comm.). These resources are given to carry out research and demonstration projects, as well as to develop handbooks, before giving full support to this technology (pers. comm. Aranda). There are several economic schemes, but the funds are insufficient to cover the demand and only 37% of all the applications are supported (Rivera pers. comm.). CONAGUA utilizes the taxes collected from the discharge fees to provide credits for water related projects, but priority is given to drinking water and increasing the sewerage capacity (Comisión Nacional del Agua, 2010). SAGARPA provides grants to adopt vermicomposting, but they are limited to agricultural projects developed by farmers (Velazco pers. comm.).

5.2.1.3 Political factors

Importance given to stabilizing sewage sludge: The stabilization of sewage sludge should be considered as a priority in order to solve the problem of sanitation. Politicians should recognize that the removal of toxic constituent from wastewater is passed to sewage sludge during the treatment operation. Therefore, an integral solution to the sanitation problematic shall consider the sewage sludge stabilization as an important part of the treatment system. Although policy makers were not contacted in this study, all the stakeholder groups consider that the treatment of sewage sludge is a low priority issue in the political agenda. Regarding the support for sanitation, priority is given to potable water, followed by increasing the sewage system coverage and installing wastewater treatment plants (de Anda, J. & Shear, H., 2008). Therefore, the treatment of sludge is often a missing part in the operation of sewage works (LeBlanc, 2008). Currently, only 5% of the total sewage sludge produced in the country undergoes an stabilization process (Ortiz-Ojeda pers. comm.).

Regulations and law enforcement: There shall be strict regulations and legal enforcement regarding the stabilization of sewage sludge. The regulatory compliance shall be monitored and sanctions shall be given to those who do not meet the stabilization standards. In addition, these regulations should consider vermicomposting among their authorized treatment alternatives (Loaiza pers. comm.). Although the treatment and disposal of sewage sludge is regulated in Mexico, half of the informants from this country considered that they are flexible and poorly enforced. They do not establish sanctions for incompliance events and pathogen stabilization is only mandatory if the sludge receives a further use. A list of treatment alternatives for vector control is suggested, but vermicomposting is not among them (NOM-004-SERMANAT-2002).

Political awareness and support: Ideally, policy makers would support this technology if they knew about it and understood its main advantages and disadvantages (Ashbee, Delgado, Ismail and Romero pers. comm.). Policy makers would be attracted by the potential of this technology so solve the sanitation and waste management problem and additionally reduce the dependency on important chemical fertilizers, create jobs, and prevent land degradation (Ashbee, Aranda, Delgado, Holcombe, Ismail pers. comm.). However, Romero claims that the use of this technology in sewage sludge should only be motivated by sanitation and environmental purposes, and not seen as a business opportunity (Romero pers. comm.). "It can produce income, but if revenue is the main or only reason to adopt this treatment, the project may well fail" (Romero pers. comm.). Currently, the technology is still unknown to policy makers. It is not supported as an alternative treatment for sewage sludge. In addition, the lack of demonstrative cases makes it difficult to get political support. "They have to prove that the technology is effective and efficient before supporting it" (Budzich pers. comm.).

Institutional support: A greater diffusion of the technology could be obtained through the support from government institutions. There should be an inter-institutional compromise and collaboration to solve the sanitation and environmental problems of the country. Institutional policies and actions should be integrated and consistent with regulations. Furthermore, in order to support the adoption of this technology, government needs to know vermicomposting and the vermicomposters (Aranda pers. comm.). However, the lack of consistency among national policies does not allow a more widespread demand for organic fertilizers. The sewage sludge produced in Mexico has been recognized as usually non-toxic and highly valuable as organic fertilizer (Oropeza, 2006) and Mexican regulations allow its reuse provided they comply with the allowable limits established in NOM-004-SEMARNAT-2002. In contrast, SAGARPA largely subsidizes the use of inorganic fertilizers as part of its development programs for the agriculture sector (Muñoz, C., 2003; Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, 2010). There is a recent interest from SAGARPA to support vermicomposting due to the increase in the price of the subsidized fertilizers but their lack of basic information about vermicomposters does not allow an initial approach (Aranda and Velazco pers. comm.). Therefore, up to date, efforts to promote the diffusion of this technology are limited to research centers (academic institutions and IMTA) and CONAGUA.

Municipal leadership: The municipal authority could be a starting point to diffuse vermistabilization. However, municipalities are driven by public image (*see* Chapter 4, Section 4.1.6) and would need policy support from reputable parties (other government agencies, research centers and academia) in order to validate their proposals and adopt this technology (Félix and Santos pers. comm.). Currently, few municipalities have taken the leadership role to innovate and are currently testing the vermistabilization performance in small-scale pilot projects (Cardoso pers. comm.).

5.2.1.4 Technical factors

Discharge characteristics: Current developers recommend that industrial and domestic discharges should not be mixed in order to prevent the addition of chemical constituents and heavy metals to the sludge (*see* Chapter 2, Section 2.3.2). In this sense, Mexican sewage sludge is adequate for the treatment as these two discharges are usually separated before reaching the sewerage. Nevertheless, irregular events may occur due to the lack of inspection by the authority (Cruz-Ojeda pers. comm.).

Sludge production regime: Worms are voracious eaters and require continuous inputs of food (*see* Chapter 2). A continuous production and supply of sewage sludge is necessary to maintain optimum vermicomposting conditions. Therefore, vermicomposting should not be considered as an option to stabilize the sludge from wastewater treatments operations with an intermittent sludge generation. Although national averages (*see* Figure 3-1) indicate that wetlands are not a common treatment, they are a popular and cheap wastewater treatment alternative in the poorest regions. For instance, the State of Oaxaca reports that wetlands provide treatment to 27% of their wastewater (Cruz-Victoria pers. comm.). Thus, although the low costs of vermicomposting may be attractive, some investment is needed from the side of the wastewater treatment process to guarantee a continuous output of sludge.

Sludge characterization: The non toxic characteristics of sewage sludge shall be determined on regular basis by laboratory analysis. Although worms are usually tolerant to a high variety of pollutants, sludge has to be characterized as a precautionary measure to prevent toxic or lethal exposures (Romero pers. comm.). Currently, toxicology analysis for sewage sludge are carried out in external laboratories, but are not focused on the main toxic constituents for the worms.

Contingency procedure: Mexican regulation NOM-004-SEMARNAT-2002 requires a periodical determination of the toxicological characteristics of the sludge on a trimestral, semestral or yearly basis, depending on the volume of sludge produced. This allows the identification of toxic sludge with a specific frequency. In general, the characteristics of the sewage sludge in Mexico have proven not toxic (de Anda, J. & Shear, H., 2008; Jiménez, B. & Wang, L., 2006; LeBlanc, 2008). Nevertheless, a contingency plan should be previously defined in order to respond to potential contamination that shall put into risk the survival of the worms.

5.2.2 Sewage sludge treatment

5.2.2.1 Management factors

Treatment location: The vermicomposting treatment should be installed on a flat ground conveniently located near the sludge producer and humus user to avoid excessive transportation costs. Installations within the wastewater treatment facility or very close to it would be ideal. The access to a water supply should be considered, as moisture control is one of the main operational parameters. Low agricultural value land would be an ideal place in order to avoid competition against crop production. Up to date, only small-scale projects have been installed that are easily located within the existing facilities. However, the characteristics of the treatment location should kept in mind for future facilities, especially in arid regions were water is scarce and in places with highly valuable agricultural land. Current developers report that transportation costs can significantly increase the operational cost of the treatment and make its economics inconvenient (Aranda pers. comm.). Therefore, the decision to install an off-site vermicomposting facility should be carefully analyzed.

Long-term management system: The administration of a vermicomposting process shall be organized as any other enterprise with a long term planning vision to make it operate efficiently (Delgado per. comm.). It shall define clear roles and responsibilities and consider operational procedures and controls at all levels of the organization. Decisions shall be taken accordingly to guarantee the survival of the project. A management system if this kind would consider potential expansions to the wastewater treatment facility in advance in order to evaluate its adaptation and/or survival to major changes. In addition, an effective logistics system shall be implemented to avoid shortages or excessive storage of raw materials and worm castings. The basic equipment for the process should be subject to inspection and maintenance routines and spare parts should available or easy to obtain. Currently, there is not enough information to evaluate this item for the pilot facilities. However, experience indicates that other vermicomposting operations for different wastes, in Mexico, failed in the past because their management system could not guarantee a continuous provision of feedstock (Aranda, Romero pers. comm.). On the other hand, several wastewater facilities experience problems related to the provision of spare parts due to budget limitations (Ramírez and Santos pers. comm.).

Human resources: Depending on the scale and design of the treatment, vermicomposting may be a labor intensive operation (see Chapter 4, Section 4.2.8). However, sufficient operators shall be hired according to the needs of the operation. Operators may be hard to find, especially in urban areas. Current adopters identify ideal operators as people with affinity towards farm-related work. On the other hand, facilities (especially municipalities) experience problems of high turnover ratios due to low wages and poor working conditions (Ramírez and Santos pers. comm.).

Training: As discussed in Chapter 4, basic training in vermicomposting is easy and not expensive at the operator level. However, more technician treatment should be provided to the potential developers and main process supervisors at the treatment facility. Currently, training on vermicomposting is given by current developers, IMTA, and some academic institutions. Although several books explaining the basis of the operation and design, there is the need for standardized training programs, operational handbooks and design criteria (Aranda pers. comm.).

5.2.2.2 Economic factors

Budget: Sufficient budget should be assigned to cover all the fixed costs, contingencies and salaries. In reality, municipal wastewater treatment plants operate under limited budgets (Santos pers. comm.). Approximately, 39.5% of the municipalities in Mexico have a high to very high poverty grade (de Anda, J. & Shear, H., 2008). These are usually small communities that cannot afford expensive treatments and have to minimize operational costs. On the contrary, big cities have sufficient economic resources to install sophisticated treatment alternatives. Therefore, small municipalities could be considered a target group to diffuse vermicomposting (Ojeda pers. comm.). Usually, small plants utilize an aerobic digestion system that is highly energy consuming and does not allows energy recovery. However, municipalities with enough budgets to invest are looking towards anaerobic digestion in order to produce power from the methane production. The municipalities that have already installed anaerobic digesters would hardly change their technology. They are more attracted to energy recovery projects than to producing fertilizer.

***Competition*:** In order to promote the diffusion process, policy makers should not be negatively influenced by external pressure from the already established business sectors competing with vermicomposting. Current developers identify the "waste to energy" paradigm as a barrier for the diffusion this technology (*see* Section 4.2.13). When economic resources are available, large wastewater treatment facilities with anaerobic digesters prefer to produce biogas. As shown in Box 5-1, "waste to energy" economic benefits from anaerobic digestion depend on the size of the plant. The production of biogas can be attractive for large-scale facilities (> 50,000 population equivalent). On the contrary, there is a negative balance for small wastewater treatment plants (1,000-30,000 population equivalents) between costs and revenue since digesters operating at low loads yield poor biogas volumes. Small-scale vermicomposting does not affect the economic interests of the "waste to energy" industry. Although aerobic treatment is the preferred option at small-scale facilities due to its high removal rate of organic matter, the bacteriological constituents are not destroyed. On the other hand, alkaline stabilization requires a high input of chemicals, producing a high operational cost while it only temporarily eliminates the biological load. Thus,

"Vermicomposting is starting to gain a greater relevance as a treatment alternative for small wastewater treatment plants where the implementation of conventional treatment technologies would be expensive and inefficient"

(Dr. Cruz-Ojeda, CONAGUA, pers. comm.)

Box 5-2 Waste to energy costs from anaerobic digestion

Waste to energy costs from anaerobic digestion
(average US wastewater treatment plant)

Costs:

- Capital investment and operational costs: €70-105/p/year

Income:

- Taxes and fees for wastewater treatment: € 38-55/p/year.
- Green certificates: €7.1-7.8/p/year.
- Co-processing other waste: €16.67/p/year (municipal waste), €1.6-1.8/p/year (other organic waste).

Source: (Pavan, Bolzonella, Battistoni, & Cecchi, 2007)

Economic performance: Operational costs of vermicomposting should be as low as possible in order to compete with existing technologies. Stakeholders identify this element as one of the strongest drivers for the adoption of this technology (*see* Chapter 4). In addition, the full-scale implemented project should stand alone without the need of economic incentives in order to be considered a success (Holcombe, pers. comm.). Currently, no incentives are being provided to support the installation and operation of this technology. However, as discussed in Chapter 4, economic incentives are perceived as helpful but not necessary to adopt this operation. As mentioned by Santos, savings are already a highly enough economic incentive. Nevertheless, more facilities should be installed in order to have an idea of the average operational and investment costs (Ashbee, pers. Comm.) Up to day, there are no formal studies that could be considered representative of the sewage sludge operation due to the limited historical and operational data. Cardoso *et al* have reported the capital investment and operational costs for small-scale systems in Mexico (Cardoso, L., Ramírez, E., & Escalante, V., 2008). In addition, Appendix 3 compares the costs and savings of the projects developed by the informants participating in this study. However, none of these figures should be considered a reliable source for a cost estimation of the project due to the different characteristics of the treatment facilities.

5.2.2.3 Political factors

Diffusion: Loaiza affirms that more pilot tests and full implementation projects should be developed in order to increase the trust on this technology and promote its good performance base on scientific evidence (Loaiza pers. comm.). This would facilitate the diffusion of this technology. Santos affirms that the diffusion process requires significant inputs of economic resources only available for governments and big corporations (Santos, pers. comm.). Successful pilot scale projects are already being developed in Mexico, but these projects are not receiving the support from the government or the big corporations. Instead, the technology is being diffused by small-scale developers and adopters that assume the role of spreading the technology within domestic adopters and private organizations (pers. Comm. Aranda, Carrera, Delgado, González, Haros and Romero). Current adopters share their experiences in seminars, workshops, and facility tours, while developers publish books, organize or participate in conferences, offer training and conferences and some of them promote their activities in online sites. Nevertheless, their diffusion capacity is limited since they do not have access to massive communication channels. According to SAGARPA, the diffusion of vermicomposting has been successful within the agriculture sector due to its presence and communication in the technology exhibitions (Velazco, pers. comm.).

Continuity: The survival of the vermicomposting facilities should be independent of the political parties in power. Usually, the continuity of the projects supported by public funding depends on politicians and election periods. Projects are often started and abandoned after the change of power or when they run out of money (Aranda pers. comm.). There is not enough information to evaluate the continuity potential of the existing projects. However, Holcombe affirms that public and private facilities would survive if they were self-sustained without external economic inputs.

Vermicomposting social image: The vermicomposting treatment shall create a positive image in order to be accepted by the society. For municipal sewage works, this element is a strong driver to adopt this technology (see Chapter 4). Current adopters report that the vermicomposting system creates an extremely positive image to the organization because society perceives it as a “cradle to cradle” solution and relates the production of worm humus to food security. However, the currently positive image of vermicomposting is fragile due to the little knowledge about this technology. Technical factors
Operational performance:

The implementation of vermicomposting projects should be based on the optimum operational method and controls defined by pilot tests. There are very few to vermistabilization facilities in operation to demonstrate the effectiveness of the treatment. Most of the projects in Mexico have been developed at laboratory scale with a research purpose. Small-scale pilot projects are being implemented by IMTA in rural wastewater treatment plants with a capacity below 10 liters per second (Cardoso, L. et al., 2008). In addition, few private companies are also adopting the treatment at their facilities for small loads. There is one municipality in Guanajuato running a small pilot project of a medium size facility. In addition, most of the municipal sewage works participating in this study affirmed to be interested in running pilot tests for their waste (Santos, Loaiza, Hernández, pers. comm.). More installed facilities with successful performance would help to diffuse this treatment alternative.

Land requirements: The installed capacity of the facility should be adequate for the volume of waste being treated (considering seasonal peaks). As discussed in Chapter 4, the adoption of vermicomposting sometimes is limited by land requirements. Many wastewater treatment plants do not have enough space to accommodate this treatment at their facilities (Cardoso and Cruz-Ojeda pers. comm.). Land requirements can vary depending on the design characteristics and they can become a barrier. In Mexico, several worm farmers adopt an extensive vermicomposting design; while more effective intensive vermicomposting demand less space by increasing their operational performance (*see* Chapter 2).

Feedstock inspection: The sludge and bulking agent should be inspected upon arrival to verify that they meet the process requirements. In addition, a local supply of bulking agent must be guaranteed should it be needed in the process. A sufficient and quality feedstock supply is vital for the long-term survival of the process. The failure to meet this requirement is one of the main reasons behind unsuccessful vermicomposting experiences in Mexico (Aranda and Romero, pers. comm.).

Processing methods: The selection of the processing method shall consider a balance between efficiency and simplicity. Efficiency can be understood as lower land requirements; labor demands and/or residence time (*see* Chapter 2). While lower land and labor requirements could be met through mechanization, this method would add a higher complexity to the treatment and additional investment and operational cost. Although mechanized methods are being developed in the US, Austria and Australia, in Mexico adopters have preferred simple systems. Stakeholders identify the treatment simplicity as one of the main drivers for adopting this technology. Thus, the simpler the process is to operate and understand, the better it will be received.

Control parameters: The main operational controls shall be maintained within the operation range described in Chapter 2. The facility should be able to perform on-site measurements and analysis for all the control variables. Water inlets should be installed to keep the moisture under control. Sufficient bulking material (quantity and frequency) should be available for the process. The population of worms should be able to process the total amount of wastes. In cold climates, the facility shall be provisioned with heating systems. The controls should also consider the management of excessive quantities of worms. Although the reproduction will auto regulated as they approach the carrying capacity, worms shall be monitored to determine excessive concentrations of heavy metals and other toxic chemicals. Worms will bioaccumulate any toxic material found (*see* Chapter 3). Thus, the system has to be "purged" to eliminate the excess of worms and regulate the bioaccumulation of contaminants (Aranda, pers. comm.). In simple systems, the main operational parameters are not hard to monitor and measurements do not require sophisticated equipment.

Equipment and machinery: All the necessary process equipment and machinery shall be available at the facility and they shall be adequate for the local conditions. Simple small-scale systems can be operated with regular gardening tools. However, the operation becomes more complicated as the treatment scale grows and some machinery will have to be introduced to facilitate the process. One of the typical failures of any treatment process is the lack complete equipment and/or spare parts (Ashbee, and Santos, pers. comm.).

Technical support: The design and installation of a vermicomposting facility must be supported by experts in this field. Currently, most of them are researchers and worm farmers that provide consultancy as a side activity of their main business occupation. There are not vermicomposting professionals in the wastewater industry. However, the selection of these treatment processes is usually done by the designer of the wastewater treatment plant. Thus, potential adopters interested in this technology usually have to look for the current developers, but they are not as easy to contact as the technical experts from the wastewater sector are. Therefore, the wastewater treatment industry, currently dominated by engineers with no knowledge about earthworms, shall develop some expertise in vermicomposting in order to diffuse this technology.

5.2.3 Sewage sludge disposal

5.2.3.1 Management factors

Distribution channels Currently, there are no formal distribution channels for the worm humus from sewage sludge. In addition, municipalities are uncertain about what to do with the production of humus and the excess of worms. Velazco considers that there is a greater potential to create distribution channels in the north of the country because the soil is less fertile and land presents erosion and pollution problems. The lack of distribution channels can be considered an impediment for the adoption this technology. Padilla affirms that this is one of the main reasons that would prevent his facility from adopting this treatment. According to Padilla, the investment in vermicomposting is not justified in a cost-benefit analysis when many resources are invested in produce a high quality fertilizer that will end up in the landfill.

Market for commercialization: If commercialization is considered, there should be a market to commercialize the humus production. The current market for worm humus is informal and unstable because price has not been regulated. Changes in public policy and attitudes regarding the use of non-organic fertilizers and pesticides are creating significant market opportunities for the use of worm castings as a replacement (Ashbee, pers. comm.). However, Velazco considers that farmers would be reluctant to accept humus from sewage sludge because of the strict sanitary regulations to vegetables, although there could be some potential to use the worm castings with grain crops (Velazco pers. comm.). The lack of research demonstrating that the product is safe creates uncertainty among potential users.

5.2.3.2 Economic factors

Revenue: Government should intervene to formalize the existing market. Regulations shall be created to control the price of worm humus (Aranda, pers. comm.) In addition, if commercialization is considered by the municipalities, a procedure shall be previously designed and approved to control the cash flow of the revenue. These regulations have not been created yet. Vermicomposting has been seen as a profitable opportunity by many. While the sale of humus it can be attractive, its profitability is unstable due to the lack of a formal and structured market. Details about the stakeholder's viewpoints regarding market prices are presented in Section 4.1.3. For municipal wastewater treatment facilities, selling the product is not an alternative easy to carry out due to the different nature of their assigned responsibilities.

Competition with agrochemicals: The business sectors affected by the humus utilization should not influence negatively on policy makers to avoid the diffusion of this technology. Instead, support should be given to increase the demand for humus. Under the current system paradigms, organic and inorganic fertilizers are both being used by farmers as complements (Aranda and Romero pers. comm.). However, there is an indirect competition created by the government policies that support to the consumption of inorganic fertilizers through price subsidies, whereas organic fertilizers are not being promoted (Muñoz, C., 2003; Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, 2010). Mexican farmers depend on agrochemicals. Few farmers utilize organic fertilizers, although ranchers are slowly adopting the treatment as part of their business activities (pers. comm. Rodríguez). Nevertheless, the application of fertilizers from sewage sludge is still uncommon (pers. comm. Rodríguez).

5.2.3.3 Political factors

Support and promotion: Some reaction should be expected due to the nature of the sludge. Therefore, this humus should not be expected to survive in the market without government support. (Aranda). The benefits of vermicomposting shall be recognized and promoted. Support shall be given to guarantee the long-term demand for humus and increase its demand. The policy makers have to join hands with technologists to promote composting/vermicomposting of sludge to convert it to a socially acceptable soil amendment. If this importance is made clear to policy makers, it will become easy to sell the technology (Kale, pers. comm.) and its end product.

Regulations: Several regulations shall be created to support this new technology. These regulations include setting controls to the market price for worm humus, and determining the quality characteristics of the worm castings, the maximum load rate to the soil, and the authorized disposal methods. Regulations shall clearly define the cases in which the worm humus from sewage sludge should not be utilized. The quality of the worm humus from organic waste has already been defined by the recently published NMX-FF-109-SCFI-2008 rule, but it existence is still unknown to several vermicomposters.

5.2.3.4 Technical factors

Product inspection: The stabilized worm humus should be analyzed after the vermicomposting operation in order to monitor its quality and safety. This is not a common practice that increases the operational costs. However, laboratory analysis to prove the safety of this product will contribute to create trust and acceptance among the potential end users.

End use: Research shall be made to find viable and safe disposal methods. Small-scale operations have not found problems to give and end use to this product. The worm humus is mainly used for landscaping applications within the treatment facility. Whenever excess of humus is available, the product is given freely to the community (Delgado, González and Haros, pers. comm.).

Product standardization: The characteristics of the end product should be standardized. Currently, worm humus is produced with heterogeneous compositions due to differences in sludge characteristics, vermicomposting designs and operational methods. The widely difference in quality decreases the consumer's trust on the product. However, the recent Mexican regulation NMX-FF-109-SCFI-2008 establishes an average quality of worm castings and prohibits the production using hazardous sludge (according to the limits set by NOM-052-SEMARNAT-2005).

5.3 Evaluation of the adoption and diffusion system

This Section summarizes and evaluates the 41 elements identified as necessary for an ideal adoption of vermicomposting in sewage sludge. The evaluation is based on the stakeholder's viewpoints presented in Section 5.2. The comparison table described in Chapter 1 was used in order to identify the main areas with opportunities for improvement and recognized those with the greatest maturity. The maturity level is defined by the number of elements already in place in the stage or factor being evaluated. Thus, from the evaluation shown in Table 5-1, it can be noticed that there is not a strong structure within the current system to allow a successful adoption, diffusion and long-term survival of vermicomposting. Detailed observations are presented as follows.

5.3.1 Main strengths

In general, this evaluation has identified the treatment stage as the strongest area of the overall sewage sludge treatment system presented in Figure 5-1. Although this stage is not fully mature, most of its elements are already set in place or under development. The greatest maturity in the system was identified among the technical elements at the production stage. Except for the lack of a contingency plan, the stage of production can provide continuous and adequate (non-toxic) sewage sludge to the treatment stage.

5.3.2 Main opportunities for improvement

The greatest opportunity for improvement was found at the management of the sewage disposal stage. There are no formal distribution channels or markets to commercialize the product. Although there might be a demand, lack of communication has limited the identification of distribution networks. Municipalities participating in this study expressed their concerns on this issue. For Padilla, the lack of an end use for the product can result in a barrier for its adoption since resources are spent in producing a valuable fertilizer that will not be utilized. The lack of current political support to the usage of organic fertilizers, especially those made from sewage sludge, makes it difficult to find end users. Government should intervene to facilitate the identification of distribution channels and increase the trust on the worm humus from sewage sludge. Regular quality inspections based on laboratory analysis and background research demonstrating its safety would help to increase its commercial acceptance or reduce the reaction from major potential users (e.g. farmers, parks, urban gardens, etc.).

Political support is also needed to allow a fair market competition. The technology would only compete with "waste to energy" technologies if developed at large scale. However, at the moment, vermicomposting is not affected by this potential competitor since the technology is being adapted for small-scale projects only. Given the infant stage of this technology, it will take time before the adoption of large-scale treatments is discussed. However, competition with agrochemicals is an important area where policy changes may stimulate the diffusion of vermicomposting.

Finally, very important elements that attention are the lack of massive communication channels and support for diffusion. This study has found that the flow of information among the stakeholder groups is poor. The communication networks have not been constructed. This is a necessary element to allow the diffusion of this technology. At the moment, without these communication channels and flow of information, current adopters and developers are hard to find. Although the trainings offered by IMTA and CONAGUA are helping to spread some information about this technology, effective communication needs a greater flexible and diversity of channels.

Table 5-1 Evaluation of the vermicomposting adoption system.

Factor	Stage 1		Stage 2		Stage 3	
	Description	**Eval**	**Description**	**Eval**	**Description**	**Eval**
1. Management	1.1.1 Sludge production records	△	2.1.1 Treatment location.	✓	3.1.1 Distribution channels	✕
	1.1.2 Communication channels	✕	2.1.2 Long-term management system.	-	3.1.2 Market for commercialization.	✕
			2.1.3 Human resources	△	3.1.3 Establish communication networks for disposal.	✕
			2.1.4 Training	✓		
			2.15 Social image	✓		
2. Economic	1.2.1 Economic incentives to produce non toxic sludge	△	2.2.1 Budget	△	3.2.1 Revenue	△
	1.2.2 Economic incentives to adopt vermicomposting	△	2.2.2 Competition	△	3.2.2 Competition with agrochemicals	✕
	1.2.3 Expected costs	✕	2.2.3 Economic performance	✓		
3. Political	1.3.1 Importance given to stabilizing sewage sludge	✕	2.3.1 Diffusion	✕	3.3.1 Support and promotion	✕
	1.3.2 Regulations and law enforcement	△	2.3.2 Continuity	△	3.3.2 Regulations	△
	1.3.3 Political awareness and support	✕				
	1.3.4 Institutional support.	△				
	1.3.5 Municipal leadership	△				
4. Technical	1.4.1 Discharge characteristics	✓	2.4.1 Pilot testing	✓	3.4.1 Product inspection	✕
	1.4.2 Sludge production regime	✓	2.4.2 Land requirements	△	3.4.2 End use	△
	1.4.3 Sludge characterization	✓	2.4.3 Feedstock inspection.	△	3.4.3 Product standarization	✕
	1.4.4 Contingency procedure	✕	2.4.4 Processing methods	△		
			2.4.5 Control parameters	△		
			2.4.6 Equipment and machinery	✓		
			2.4.7 Technical support	△		

EVALUATION

- ✓ In place
- △ In progress (needs improvement)
- ✕ Not done yet
- \- Not enough information to evaluate

5.4 Potential for adoption

Vermicomposting is a technology at its infant stage, but with the potential of future development at small scale. The system dynamics matches the models proposed by Rogers in Chapter 2. As can be seen from the evaluation, there is not a linear and rigid sequence of events that pull the development and diffusion of this technology, but a mixture of several different elements interconnected in a complex structure. The development of this innovation supports the innovation adoption theories in the roles assumed by its participants. The dynamics leading to the adoption of this technology at is immature stage are mainly dominated by the small group of early adopters, supported by small-scale producers. Potential technology developers do not play an active part in the current diffusion of vermicomposting. Likewise, policy makers stay apart and government institutions do not fully provide the necessary support the diffusion efforts. The institutional and political support for this technology could increase in the future if more small-scale pilot projects were run with success at a municipal level. However, most municipalities are usually not willing to take the risk without political support. Although potential adopters from the private sector were not considered in this study, their viewpoints would be useful at this point to complement this discussion. Should they expresses a similar interest in running small pilot tests, private users could become a clear opportunity for diffusing this technology.

An important difference from this system to the model explained by Raasch (see Chapter 3) is the lack of massive communication channels. The flow of information among the potential actors is still relatively low, although they all have established methods to communicate their experiences and are willing to share their knowledge freely with other potential adopters. Yet, it is not clear what the optimum information media should be.

6 Conclusions

The previous chapters have presented the results from the research on the "Potential for the adoption of vermicomposting to stabilize sewage sludge in Mexico". The aim of this research was to identify the current main drivers and barriers for the use of earthworms to stabilize sewage sludge in order to determine the potential for a greater adoption of this biotechnology in the wastewater treatment industry. The research gathered the viewpoints of five key stakeholders: current and potential technology adopters, current and potential technology developers and government institutions. Whenever possible, viewpoints were supported with data collected from literature review. Section 6.1 presents the conclusions from this research by answering the sub research questions. In addition, Section 6.2 offers general recommendations based on the model presented in Chapter 5 are presented.

6.1 Research objectives

Objective 1: *To assess the current state of vermicomposting adoption.*

The adoption of vermicomposting for sewage sludge is still at an immature stage. Research is being made at laboratory scale with the intention to demonstrate the effectiveness of this technology in the Mexican sewage sludge. Up to date, the research on this topic is led by academic institutions and public research centers. There are few small-scale demonstrative projects in the country developed within the public and private sectors. However, these projects have not provided sufficient and valuable historical data regarding operational performance and treatment economics. The influence of these projects on other potential adopters is still unclear.

The diffusion of the technology is slowed down by the lack of communication networks among the stakeholder groups. Although public sponsored projects are being documented in form of reports and scientific papers, the experiences from the private facilities are not communicated in printed media. Operational problems and other difficulties that shall be taken into consideration in order to allow a continuous improvement of the treatment design have not been shared. Despite the willingness of current adopters to freely share their experiences and support the diffusion of this technology, effective communication channels have not been created. Current adopters have not created groups or associations to share their experiences. However, given their limited resources, current adopters and developers need the support of a stronger institution behind in order to diffuse the technology. Moreover, inter-institutional communication does not exist and government institutions work with disconnected and contradicting policies even that do not allow them to recognize common interest points.

The weakness of the disposal stage. There is a lack of a formal distribution channel for the worm humus from sewage sludge. Although the product has proven safe during the pilot tests, regulations for its safe usage are needed in order to establish application loads and quality controls. The latter would also result in a greater confidence from potential end users that would allow the creation of distribution channels. The current regulatory framework is not suitable for the introduction of this technology

Competition with stabilization by solar drying. Solar drying is also a land demanding operation, but it is recognized and supported by the Mexican regulations. In addition, solar drying is cheaper, simpler and currently utilized by several municipalities. Vermicomposting would find it hard to compete against this technology in a cost-benefit analysis unless excessively wet climate conditions did not allow the successful implementation of solar drying, or the interest in a top quality organic fertilizer was strong.

There is some knowledge about vermicomposting. Although the technology is at its infant stage, most of the interviewees had a least a basic idea about the treatment. Some of them had received information from the trainings by IMTA, but most of them received the information from a different channel that this research failed to identify.

Objective 2: *To identify and evaluate the main drivers and barriers preventing the diffusion of vermicomposting.*

Drivers: Lower costs and savings were identified as the main drivers, together with process simplicity, legal compliance and the ease to find and train operators. This implies that the current system identifies the need of providing stabilization using cheap and simple technologies. In this way, vermicomposting may have a potential for a greater future development.

Barriers: The main barriers identified were related to uncertainty. The lack of more pilot projects and historical data leaves several questions regarding costs, performance and operational controls under the Mexican conditions without an answer. Additional barriers suggested by the stakeholder groups were complicated operational logistics, waste to energy paradigm, influence of current wastewater treatment designers and lack of communication channels.

As mentioned in the literature review, potential developers from the wastewater industry can be a barrier. They are the main actor in the selection of the treatment alternatives for sewage sludge under the current system. Once the treatment is installed, it is difficult to adopt a new technology because investment has already been made.

Objective 3: *To determine the willingness of adopting a vermicomposting system instead of the conventional treatment alternatives.*

a) Potential adopters

Municipal plants with conventional technologies expressed their interest in running pilot tests. There is an interest in adopting more sustainable and cheaper technologies. However, their final decision will be based on a cost-benefit analysis. Unless the economic savings for adopting vermicomposting are significantly high, this may raise a discussion upon the need to spend additional resources and change current paradigms to produce a high quality product that does not have a productive final end (if distribution channels are not created). There is some concern about the potential reaction from society due to the nature of the sludge. However, this discussion cannot be fully addressed without performing another survey among potential humus users and doing a market study. Nevertheless, the experience from Denso tells that, despite the employees being aware of the nature of the sludge, the worm humus is on high demand.

b) Potential developers

Potential developers will not be interested in participating in the diffusion of vermicomposting unless it becomes a proven technology, receives support from the authorities, and represents a good business opportunity for their operations. Potential developers are mostly engineers. Their lack of understanding about living organisms creates a barrier for the adoption of this technology, as they do not feel comfortable working outside their knowledge area. In general, the role assumed by this stakeholder's group matches the theoretical models suggested by the literature. Therefore, no special contribution is expected from this group to the diffusion of vermicomposting in the short run.

c) Government

Public institutions related to the wastewater sector are interested in supporting the development of this technology at small scale. Their support is mainly offered in the form of research, development and technical advice, although some limited funding could be available for small projects. However, the stabilization of sewage sludge is not perceived as a priority before other urgent social needs. Therefore, economic support from government institutions is not expected to be high.

Objective 5: *To determine conditions for adoption of vermicomposting.*

Table 5-1 from Chapter 5 presents the list of elements identified as important for a successful long-term adoption of vermistabilization, based on the stakeholder's viewpoints.

Currently, there is potential to develop the treatment at a small scale supported by the current/early developers. There are economic incentives to run small pilot projects, but the grants may be difficult to obtain as the funds are distributed among a high variety of projects.

However, due to low experience with demonstrative projects, the development of vermicomposting depends on the innovative desire of the adopters. Even though both types of potential adopters may be driven by innovation, private companies are less restricted by budget and social image. Therefore, it could be easier for them to adopt pilot projects within the private sector.

It is important to keep in mind that vermicomposting is a holistic cradle-to-cradle solution, but can have a significant footprint. This is a good alternative to solve sewage sludge management problems, but it is not a solution for anyone. Therefore, the decision to adopt this treatment should be based on a cost-benefit analysis. Sufficient land should be available and restrictions to the final use and application loads of the worm humus should be set as a precautionary measure.

6.2 General policy recommendations

Policy recommendations have been already introduced and discussed in previous sections. They can be summarized as follows.

1. Policy consistency among institutions and work plans. Current policies recognize the need to provide sanitation, contribute to the conservation of the environment and pollution remediation, food security and employment. These aims are not conflicting among themselves. However, the current policy framework creates incentives and programs disconnected from the interests and needs of the other institutions. Moreover, the policy impact in other public areas is not analyzed.

2. Institutional empowerment: Institutions need to receive more responsibilities in order to increase their interest and compromise towards the solution of national problems. In addition, they need to be provided with enough resources to operate efficiently. Currently, government institutions are restricted by limited budget and lack of human resources.

3. Creating more strict regulations for the adoption of a treatment. Force to adopt an effective treatment and meet minimum Class C requirements. Industry will be forced to adopt a treatment and will look for the cheapest options in the market. Municipalities have to provide treatment due to high social pressure and strict control, but it is more difficult to enforce the law and monitor private users.

4. Creating the institutional framework for the utilization of worm humus. There are regulations regarding application loads, market pricing and authorized disposal methods that have to be defined in order to guarantee the long-term survival of the vermicomposting system and to avoid social reaction against this product.

5. The lock to the current system can be broken by institutional support to spread the knowledge and build communication channels.

6.2.1 Further investigation

This study has identified the need for further research in the following areas:

- Optimum vermicomposting operational performance under the Mexican circumstances for sewage sludge.

- Economics of the vermicomposting system; specifically, more information is needed about savings (both energy and waste disposal) and investment costs for different implantation scales and design methods. Benefits shall be quantified, including carbon capture potential.

- Land requirements and their potential competition for agricultural land. Potential has to be assessed based on the possibilities for expansion at the wastewater treatment facilities in order to accommodate a vermicomposting process at their current location.

- Viewpoints from potential adopters from the private industry, potential adopters from rural areas, and policy makers that were not considered in this study.

- Quantification of potential end uses and determination of the application load rates of worm humus, maximum allowable limits and restrictions to its use.

69

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71

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Appendix 1 – Semi-structured questionnaire

VERMICOMPOSTING ADOPTION SURVEY

Survey description:

The aim of this survey is to gather information for academic purposes in order to explain the factors involved in the adoption/diffusion of vermicomposting for stabilizing sewage sludge. The survey is divided into five sections.

Section 1 gathers general information about the informant for statistics purposes. Section 2 assesses the level of awareness and trust of the informant about vermicomposting. Section 3 evaluates the potential drivers and barriers for the adoption of this technology in a 5-point scale. Section 4 presents open questions classified by type of informants in order to gather additional information about their context. Section 5 (optional) leaves free space for additional remarks.

Definitions:

Informants: Individuals and organizations taking part in this survey, which can be classified as technology adopters, technology developers, and technology regulators.

Technology adopter: Individuals/institutions that have adopted (or could potentially adopt) vermicomposting for treating their waste.

Technology developers: Companies currently designing and installing vermicomposting facilities, or with the knowledge and/or willingness to do so.

Regulators/government: Government environmental agencies that regulate the efficient stabilization and management of sewage sludge.

Stabilization: sludge is considered stabilized when its pathogenic levels are reduced to below quality standards defined on a national basis, the offensive odours have been eliminated and the potential for putrification has been minimized

SECTION 1. BACKGROUND INFORMATION

Date (day/month/year): / /

1.1	Institution name:		
1.2	Location (city, country):		
1.3	Informant's position in company:		
1.4	Contact details (*please mark your preferred contact option*)	☐ Email:	
		☐ Phone:	(Country code)

Cont. VERMICOMPOSTING ADOPTION SURVEY

SECTION 2. AWARENESS AND TRUST

2.1 How important is it for you to provide an efficient stabilization for sewage sludge?

- ☐ Not necessary
- ☐ It should comply with the legal standards
- ☐ It should achieve safe levels for humans (if possible, above the legal standards)
- ☐ It should make the sludge safe for humans and for the environment (if possible, above the legal standards)

2.2 How strict are your country's regulations and/or monitoring bodies about meeting the local limits for sewage sludge stabilization?

- ☐ Very strict
- ☐ Flexible
- ☐ Not regulated/monitored

2.3 Which of the following would describe your knowledge about vermicomposting?

- ☐ I do/have done research on vermicomposting
- ☐ I can operate or design the process
- ☐ I am familiar with the basic characteristics of the process
- ☐ I have a vague idea of what it is

a) Developed countries	Yes/No	Why? *Explain*
b) Developing countries	Yes/No	Why? *Explain*
c) Private package plants	Yes/No	Why? *Explain*
d) Small sewage works	Yes/No	Why? *Explain*
e) Medium/large sewage works	*Yes/No*	*Why?* *Explain*

2.4

Do you find vermicomposting for sewage sludge viable for…?

(select)	*Other:*
Why?	

2.5 Which of the following treatment would be your preferred option for stabilizing sewage sludge?

2.6 According to your experience/perception, what are the main benefits and disadvantages of utilising vermicomposting as a treatment process for stabilizing sewage sludge?

Cont. VERMICOMPOSTING ADOPTION SURVEY

SECTION 3. EVALUATION OF DRIVERS AND BARRIERS

The following statements present a list of factors that may drive a facility towards adopting vermicomposting. Based on your opinion, evaluate their influence on the final decision and briefly explain your choice. The level of influence is evaluated in a 5-point scale, being 1-"Not influencing", 2-"Weak", 3-"Moderate", 4-"Strong" and 5-"Very strong".

DRIVERS

Perception statement	Influence	Why?
3.1 Lower capital investment and/or operational cost (as compared with other treatments)		
3.2 Savings in energy and/or waste disposal costs		
3.3 The end product has a market value		
3.4 Establish a pioneer/leadership position by adopting innovative environmental solutions.		
3.5 Positive experience of other successful adopters		
3.6 Create a positive image in the community		
3.7 Ease of obtaining skilled/trained operators		
3.8 The process avoids the generation of landfill waste		
3.9 Compliance with internal company environmental policy and/or current/future governmental environmental regulations		
3.10 Existence of economic incentives to adopt vermicomposting		
3.11 The technology is recommended by a reputable body (environmental agency, academia, NGO, etc.)		
3.12 Simple process, easy to operate and there is no need for sophisticated equipment		

BARRIERS

Perception statement	Influence	Why?
3.1 Uncertain capital investment/operational cost		
3.2 Uncertain performance		
3.3 Larger land requirements		
3.4 Lack of trained/skilled workers		
3.5 The treatment is not popular among other facilities		
3.6 Vermicomposting is more labour-intensive		
3.7 The currently known technologies have proved to work well		
3.8 Lack of economic incentives to adopt vermicomposting		
3.9 Lack of support from policies and/or regulations		
3.10 Lack of information about this technology		
3.11 Lack of control over an unknown process		
3.12 Lack of strict regulations / no need to adopt a treatment process for sewage sludge		

Cont. VERMICOMPOSTING ADOPTION SURVEY

Are there any other drivers or barriers not included in the list?

____

____

Cont. VERMICOMPOSTING ADOPTION SURVEY

SECTION 4. SPECIFIC QUESTIONS PER INFORMANT

Technology adopters - Only

4.1 Have you adopted vermicomposting as your treatment method?

☐ Yes *(go to question 4.2)* ☐ No *(go to question 4.3)*

4.2 Characteristics of the vermicomposting process installed at your facility

Capital investment	(currency)		
Annual operational cost	(currency)		
Land requirement (total area)			
Amount of treated waste			
Treatment efficiency			
Savings	☐ Energy ☐ Waste management		Reduction in energy/power units
			Reduction in waste cost
End use of the compost			

(End of section 4. Go to section 5)

4.3 If vermicomposting is not your selected type of treatment, would you consider it in the future?

(Yes / No) *Explain*: ____

4.4 How did you select your current treatment type?

☐ My organization chose the treatment alter analyzing other treatment options

☐ The treatment process was suggested by the designer of the wastewater treatment process

☐ The treatment process was suggested by the regional environmental agency

☐ Other: ____

4.5 Does your current technology effectively stabilize sewage sludge?

(Yes / No) Explain: ____

(End of section 4. Go to section 5)

Cont. VERMICOMPOSTING ADOPTION SURVEY

Technology developers – Only

4.6 Is vermicomposting among the treatment processes that you currently design or suggest to stabilize sewage sludge?

☐ Yes *(go to question 4.7)* ☐ No *(go to question 4.8)*

4.7 How easy/difficult is it to sell this technology? What kind of support is needed?

Explain: ____

(End of section 4. Go to section 5)

4.8 What are the reasons for not considering vermicomposting among your treatment alternatives for stabilizing sewage sludge?

Explain: ____

(End of section 4. Go to section 5)

SECTION 5. FURTHER OBSERVATIONS (OPTIONAL)

Use this section to include any additional remarks (comments, suggested bibliography, contact details of potential informants, or any other information that you may consider relevant for this research).

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Appendix 2 – Evaluation of drivers and barriers by stakeholder

Table A2-1 Evaluation of drivers to adopt vermicomposting by current developers

Factor evaluated		5-point scale evaluation			
		Min	Max	Avg	Level of influence
3.1	**Lower capital/operation costs**	2	5	4	**Strong**
3.2	Savings (energy/waste)	**4**	**5**	**4.9**	Strong
3.3	Humus market value	2	5	4.2	Not
3.4	Innovation leadership	1	5	3.5	Not
3.5	Successful adoption cases	1	5	3.7	Strong
3.6	Create a good public image	1	5	4.1	Not
3.7	Ease to obtain operators	1	5	3.6	Moderate
3.8	Avoid landfill	2	5	4.2	Not
3.9	**Policy/law compliance**	1	5	3.4	**Strong**
3.10	Economic incentives	1	5	3.5	Moderate
3.11	Support from external organizations	1	5	3.6	Not
3.12	Process simplicity	1	5	4.1	Strong

Table A2-2 Evaluation of drivers to adopt vermicomposting by current adopters

Factor evaluated		5-point scale evaluation			
		Min	Max	Avg	Level of influence
3.1	**Lower capital/operation costs**	**4**	**5**	**4.5**	**Strong**
3.2	Savings (energy/waste)	1	4	3.0	Strong
3.3	Humus market value	2	3	2.5	Not
3.4	Innovation leadership	2	3	2.5	Not
3.5	Successful adoption cases	4	4	4.0	Strong
3.6	Create a good public image	2	3	2.5	Not
3.7	Ease to obtain operators	1	5	3.0	Moderate
3.8	Avoid landfill	1	4	2.5	Not
3.9	**Policy/law compliance**	**4**	**5**	**4.5**	**Strong**
3.10	Economic incentives	3	4	3.5	Moderate
3.11	Support from external organizations	1	3	2.0	Not
3.12	Process simplicity	3	5	4.0	Strong

Table A2-3 Evaluation of drivers to adopt vermicomposting by potential adopters

Factor evaluated		5-point scale evaluation			
		Min	**Max**	**Avg**	**Level of influence**
3.1	Lower capital/operation costs	3	5	4	Strong
3.2	Savings (energy/waste)	4	4	4	Strong
3.3	Humus market value	3	5	3.7	Strong
3.4	Innovation leadership	3	5	4.3	Strong
3.5	Successful adoption cases	3	5	4	Strong
3.6	**Create a good public image**	**5**	**5**	**5**	**Very strong**
3.7	Ease to obtain operators	3	4	3.7	Strong
3.8	Avoid landfill	4	5	4.3	Strong
3.9	Policy/law compliance	3	5	4.3	Strong
3.1	Economic incentives	3	5	3.7	Strong
3.11	Support from external organizations	4	4	4	Strong
3.12	Process simplicity	3	5	4	Strong

Table A2-4 Evaluation of drivers to adopt vermicomposting by potential developers

Factor evaluated		5-point scale evaluation			
		Min	**Max**	**Avg**	**Level of influence**
3.1	**Lower capital/operation costs**	**4**	**5**	**4.5**	**Strong**
3.2	Savings (energy/waste)	4	4	4	Strong
3.3	Humus market value	2	3	2.5	Not
3.4	Innovation leadership	2	3	2.5	Not
3.5	Successful adoption cases	4	4	4	Strong
3.6	Create a good public image	2	3	2.5	Not
3.7	Ease to obtain operators	1	5	3	Moderate
3.8	Avoid landfill	1	4	2.5	Not
3.9	**Policy/law compliance**	**4**	**5**	**4.5**	**Strong**
3.10	Economic incentives	3	4	3.5	Moderate
3.11	Support from external organizations	1	3	2	Not
3.12	Process simplicity	3	5	4	Strong

Table A2-5 Evaluation of barriers to adopt vermicomposting by current developers

Factor evaluated		5-point scale evaluation			
		Min	**Max**	**Avg**	**Level of influence**
3.13	Uncertain costs	2	5	3.5	Moderate
3.14	Uncertain performance	1	5	3.3	Moderate
3.15	Larger land requirements	1	5	2.8	Moderate
3.16	Lack of qualified workers	1	5	3.4	Moderate
3.17	Lack of successful adoption cases	3	5	4	Strong
3.18	Labor intensive	1	5	2.4	Not
3.19	Satisfied with current technologies	1	5	3.4	Moderate
3.20	Lack of economic incentives/grants	3	5	4	Strong
3.21	Lack policy support	2	5	3.7	Strong
3.22	Lack of information	2	5	3.6	Strong
3.23	Controlling unknown process	2	5	3.5	Moderate
3.24	No strict regulations	1	5	3.6	Strong

Table A2-6 Evaluation of barriers to adopt vermicomposting by current adopters

Factor evaluated		5-point scale evaluation			
		Min	**Max**	**Avg**	**Level of influence**
3.13	Uncertain costs	5	5	5	Very strong
3.14	Uncertain performance	4	5	4.3	Strong
3.15	Larger land requirements	1	5	2.3	Not
3.16	Lack of qualified workers	1	5	3	Moderate
3.17	Lack of successful adoption cases	1	1	1	Not
3.18	Labor intensive	1	3	2	Not
3.19	Satisfied with current technologies	1	3	2.3	Not
3.20	Lack of economic incentives/grants	4	5	4.3	Strong
3.2	Lack policy support	1	4	2	Not

83

1					
3.2 2	Lack of information	1	4	2.7	Moderate
3.2 3	Controlling unknown process	1	5	3	Moderate
3.2 4	No strict regulations	3	4	3.7	Moderate

Table A2-7 Evaluation of barriers to adopt vermicomposting by potential adopters

Factor evaluated		5-point scale evaluation			
		Min	Max	Avg	Level of influence
3.13	Uncertain costs	3	4	3.7	Strong
3.14	Uncertain performance	3	5	4	Strong
3.15	Larger land requirements	3	5	4	Strong
3.16	Lack of qualified workers	4	4	4	Strong
3.17	Lack of successful adoption cases	3	5	4	Strong
3.18	Labor intensive	3	4	3.7	Strong
3.19	Satisfied with current technologies	2	4	3.3	Moderate
3.2	Lack of economic incentives/grants	3	3	3	Moderate
3.21	Lack policy support	3	5	4	Strong
3.22	Lack of information	4	5	4.3	Strong
3.23	Controlling unknown process	4	4	4	Strong
3.24	No strict regulations	3	5	3.7	Strong

Table A2-8 Evaluation of barriers to adopt vermicomposting by potential developers

Factor evaluated		5-point scale evaluation			
		Min	Max	Avg	Level of influence
3.13	Uncertain costs	5	5	5	Very strong
3.14	Uncertain performance	4	5	4.5	Strong
3.15	Larger land requirements	3	5	4	Strong
3.16	Lack of qualified workers	1	4	2.5	Not
3.17	Lack of successful adoption cases	4	5	4.5	Strong
3.18	Labor intensive	3	4	3.5	Moderate
3.19	Satisfied with current technologies	3	4	3.5	Moderate
3.2	Lack of economic incentives/grants	3	4	3.5	Moderate
3.21	Lack policy support	1	4	2.5	Not
3.2	Lack of information	5	5	5	Very strong

85

2					
3.2 3	Controlling unknown process	4	5	4.5	Strong
3.2 4	No strict regulations	4	5	4.5	Strong

Appendix 3 – Treatments comparison

Table A3-1 Land requirement, cost and performance comparison of different treatments types by informant

Source	Treatment type	Capital investment (USD)	Operation cost (USD)	Treated amount (ton/year)	Land requirement (m2/ton)	Savings (USD)	Stability
Haros	Beds	$ 100,000	$ 20,000	168	13.09	$ 23,800 in waste disposal, energy savings not measured	Class A
Holcombe	Bio-reactors	$ 50,000	$ 10,000	365	65	Savings not available	Class A
Budzich	Bio-reactors	$ 3,000,000	$ 35,000*	48	?	Savings not available	n.a.
Delgado	Beds	$ 3,000	Very low	5	29.6	Savings not available	Class A
Grand	Beds	$ 140,000	$ 126,000	1600	0.5	Savings not available	Class A
Rodriguez-Quiroz	Beds	$ 5,000	$ 6,000	?	?	$ 7,000 in waste management	Class A
Cardoso	Beds	$ 10,000	n.a.	44	16	Savings not available	Class A
Romero	Beds	n.a.	n.a.	160	2.5	Savings not available	Class A-B

* Includes power, fuel, and miscellaneous equipment/supplies only.

Appendix 4 – Land requirements

a) Calculating sludge production

Inflow (lps)	DBO (mg/L) [1]	Waste (ton/day), dry basis	Moisture [2]	Waste (ton/day), wet basis	Waste (m^3/day) [3]
10	250	0.216	80%	1.08	1.35
100	250	2.16	80%	10.8	13.5
1000	250	21.6	80%	108	135

[1] Considering typical domestic discharge of 250 mg/L (Metcalf 2005).
[2] Considering typical moisture content reported by informants (per. Comm. Padilla, Felix, Hernandez,)
[3] Assuming a sludge density of 0.8 ton/m3 (pers. comm. Santos)

b) Calculating land requirements

Land requirements are calculared based on the following assumptions:

(9) The treatment capacity is that of a typical Mexican wastewater treatment plant.
(10) The vermicomposting treatment process has a 90 days average stabilization time, as reported in the literature.
(11) The lowest, medium and highest land requirements (m^2/ton) from the information provided by the informants can be directly scaled to other designs.
(12) The land requirements provided by the informants represent the total land requirements of the vermicomposting facilities.
(13) The design criteria from the informants already considered the conditioning with bulking agents in their land estimations.

Plant size	*Plant treatment capacity (lps)*	*Waste production (ton/day), wet basis*	*Treatment residence time*	*Total waste load (ton)*	Total land requirement (ha)		
					Low footprint design (2.5 m^2/ton-month)	*Medium footprint design (16 m^2/ton - month)*	*High footprint design (65 m^2/ton-month)*
Small	10	1	90	97,2	0,0243	0,15552	0,6318
Medium	100	10	90	907,2	0,2268	1,45152	5,8968
Large	1000	101	90	9072	2,268	14,5152	58,968

Appendix 5 – Informants

MEXICO

Organization	Contact name	Email
Developers		
Instituto Mexicano de Tecnología del Agua (IMTA)	Dr. Lina Cardoso	lina_cardoso@tlaloc.imta.mx
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Humussell	Dr. Mario Carrera	marcas01@prodigy.net.mx
Adopters		
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El Colegio de la Frontera Norte / Ecoparque	Dr. Xiomara Delgado	ecoparque@colef.mx
Vigue Relleno Sanitario	Juan Pablo González	pablo.gonzalez@redambiental.com.mx
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Secretaría de Agricultura (SAGARPA) - Sinaloa	Odilon Velazco	velazco@sin.sagarpa.gob.mx

UNITED STATES

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Vermicast	John Ashbee	johnashbee@csrplus.com

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EUROPEAN UNION

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