AN IMPROVEMENT OF INDUSTRIAL SOLID WASTE MANAGEMENT SYSTEM FOR THE THAI PETROCHEMICAL COMPLEX THROUGH 3R CONCEPT

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การปรับปรุงระบบการจัดการกากของเสียสำหรับโรงงานปิโตรเคมี ในประเทศไทยด้วยหลักการ 3R

นายภานุวัฒน์ อุส่าห์เพียร

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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Thesis Title	AN IMPROVEMENT OF INDUSTRIAL SOLID WASTE MANAGEMENT SYSTEM FOR THE THAI PETROCHEMICAL COMPLEX THROUGH 3R CONCEPT
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Field of Study	Environmental Management
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การจัดการของเสียอย่างยั่งยืนได้ถูกนำเสนอมายาวนานกว่าสิบปี แต่แนวคิดนี้กลับยังไม่เคยได้นำมาประยุกต์ใช้กับอุตสาหกรรมปิโตรเคมีของประเทศไทย ดังนั้น งานวิจัยนี้จึงมุ่งไปที่การประยุกต์ใช้แนวคิด 3R ได้แก่ การลดการเกิดของเสีย การนำกลับมาใช้ใหม่ และการรีไซเคิล (3R concept) กับโรงงานปิโตรเคมีเพื่อประสบผลในการจัดการของเสียอย่างยั่งยืนให้มากขึ้น โรงงานปิโตรเคมีจำนวน 6 โรงงาน ได้ถูกสำรวจในฐานะที่เป็นโรงงานกรณีศึกษา แหล่งกำเนิดของเสีย ประเภทของเสีย และการจัดการของเสียปัจจุบันถูกทำการเก็บข้อมูล วิธีการศึกษาวัฏจักรชีวิตถูกใช้เพื่อพิจารณาถึงผลกระทบทางสิ่งแวดล้อมที่ซึ่งแนวทาง 3R ได้ถูกนำไปใช้ สุดท้าย ดัชนีชี้วัด 3R ได้ถูกนำเสนอเพื่อประเมินผลสมรรถภาพของทางเลือก 3R ในแต่ละโรงงานกรณีศึกษา ผลลัพธ์ที่ได้บ่งชี้ว่ามีแหล่งกำเนิดของเสียทั้งสิ้น 4 แหล่ง ได้แก่ (1) กระบวนการผลิต (2) การซ่อมบำรุง (3) ระบบบำบัดของเสีย และ (4) บรรจุภัณฑ์ ทางเลือก 3R ที่เหมาะสมได้ถูกนำเสนอและจัดเตรียมเพื่อใช้กับโรงงานกรณีศึกษา ผลลัพธ์ที่ได้ พบว่า ทางเลือก 3R สามารถลดปริมาณของเสียที่นำไปฝังกลบลงได้ร้อยละ 79 และ 34 ของของเสียที่เกิดขึ้นทั้งหมดในโรงงานโอเลฟินส์ และโรงงานผลิตเม็ดพลาสติก ที่เป็นกรณีศึกษา ตามลำดับ การลดลงนี้ยังเป็นผลให้สามารถลดค่าใช้จ่ายในการฝังกลบและลดการสูญเสียทรัพยากรธรรมชาติลงได้ เห็นได้ชัดว่า วิธีการ 3R ได้แสดงศักยภาพสูงของการลดของเสียสำหรับการประยุกต์ใช้กับอุตสาหกรรมปิโตรเคมี นอกจากนั้น วิธีการ 3R ไม่เพียงสามารถลดของเสียที่แหล่งกำเนิดเท่านั้นแต่ยังสามารถเปลี่ยนของเสียที่นำไปฝังกลบกลับไปยังกระบวนการรีไซเคิลได้อีกด้วย การประเมินวัฏจักรชีวิตบ่งชี้ว่าทางเลือก 3R ที่นำเสนอ สามารถลดการปล่อยก๊าซเรือนกระจกเมื่อเปรียบเทียบกับการฝังกลบ ตัวดัชนีชี้วัด 3R ในฐานะที่เป็นดัชนีชี้วัดตัวใหม่ สามารถพิจารณาไม่เพียงแต่ความสามารถของการลดของเสียที่ไปฝังกลบเท่านั้นแต่ยังให้ความสำคัญกับลำดับก่อนหลังของทางเลือก 3R ซึ่งเป็นจุดสำคัญของแนวคิดนี้

สุดท้ายนี้ ตามข้อมูลที่ได้รับจากโรงงานกรณีศึกษา แนวทางการปรับปรุงระบบการจัดการของเสียเพื่อนำไปสู่การฝังกลบที่เป็นศูนย์ ได้ถูกนำเสนอในที่ซึ่งคาดว่าจะถูกใช้เป็นแนวทางสำหรับการปรับปรุงระบบการจัดการของเสียในระดับโรงงานอุตสาหกรรม

สาขาวิชา การจัดการสิ่งแวดล้อม ลายมือชื่อนิสิต ....

ปีการศึกษา 2556 ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....

5387799920 : MAJOR ENVIRONMENTAL MANAGEMENT
KEYWORDS: INDUSTRIAL WASTES / PETROCHEMICAL PLANT / LANDFILL WASTE / 3R CONCEPT / WASTE MANAGEMENT / PETROCHEMICAL WASTES

PARNUWAT USAPEIN: AN IMPROVEMENT OF INDUSTRIAL SOLID WASTE MANAGEMENT SYSTEM FOR THE THAI PETROCHEMICAL COMPLEX THROUGH 3R CONCEPT. ADVISOR: ASSOC. PROF. ORATHAI CHAVALPARIT, Ph.D., 176 pp.

Sustainable waste management was introduced more than ten years ago, but it has not yet been applied to the Thai petrochemical industry. Therefore, under the philosophy of sustainable waste management, this research aims to apply the reduce, reuse, and recycle (3R) concept at the petrochemical factory level to achieve a more sustainable industrial solid waste management system. Six petrochemical plants in Thailand were surveyed for the case study. The sources and types of waste and existing waste management options were identified. LCA were useful for considering the environmental impact where 3R options were adopted. Lastly, the 3R Indicator (3RI) was introduced to evaluate the performance of 3R option in each case study plant. The results indicated that there were four sources of waste generation: (1) production, (2) maintenance, (3) waste treatment, and (4) waste packaging. The suitable 3R option were proposed and implemented at the case study plants. The result found that 3R options could reduce the amount of landfill waste to 79% and 34% of total waste generated in olefin case study plants and HDPE plant, respectively. This reduction would result in reduced disposal costs and reduced consumption of natural resources. Obviously, 3R methodology has shown high potential of waste reduction for applying with petrochemical industry. In addition, it can not only reduce waste at source but also divert waste from landfill to the recycling stream. LCA analysis identified that the proposed 3R option could reduce GHG emission compared with the landfill option. 3R Indicator, as the new index, can determine not only the capability of landfill waste reduction but also emphasize on the priority of 3R option which is the key point of this concept.

Finally, based on the data obtained from the case study plants, the guideline of improving industrial waste management system toward to zero landfill wastes was proposed in which it expected to be used as a guideline for improving waste management system at the factory level.

Field of Study: Environmental Management Student's Signature ....

Academic Year: 2013 Advisor's Signature ....

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At last, but not the least, I would like to dedicate my Ph.D. thesis for my grandfather, Mr. Pairat Usapein. He will live in my memories, even though he would leave this world already. His teachings and actions will be remembered in my mind forever.

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CHAPTER I

INTRODUCTION

1.1 Motivations

The principle of "3R" relates to reduce, reuse, and recycle products or resources (UNEP, 2009). It implies on the increasing of recycling rate by using recyclable material, reusing product, reduction of resources and wastes. It is a simple logic that "reduce" is emphasized as first priority, followed by reuse and recycling (Moriguchi, 2007). Nowadays, there are a variety of waste management concepts those were conducted in many countries, for example, Circular Economy in China, Zero waste in Australia, and Industrial symbiosis in Europe (Ma et al., 2014; Simboli et al., 2014; Zaman, 2014a). It could be stated that every concept has the same direction that is to try to convert waste at one point to resources at another point, which emphasizes the cycle of product as a closed loop system of resources and energy in economy systems. Also with 3R (reducing, reusing, and recycling) concept, this concept emphasizes on the closed loop of resources and energy by reusing and recycling options. However, before considering recycling option, 3R concept has to be realized in the reduction of waste at source. After that, if the reduction of waste at source could not feasible, it will lead to determine the re-use option. In many researches, 3R concept has combined with other waste management principles (for example, circular economy) to reusing waste as a new resource and reducing the pollution of disposal waste at the same time and to optimum natural resources utilization with minimum environmental burden (Wu et al., 2014; Zaman, 2014b).

To implement the sustainable waste management, in addition, we need some tools that can be applied to the enterprise level. The tool must be easily to understand for the people responsible for waste management at the factory. 3R principles or also known as the hierarchy of waste management is an important concept in the adoption of sustainable development (Taylor, 2012). 3R's is a contemporary concept to cope with the increasing quantities of waste in addition to the existing concept like clean technology, cleaner production, and industrial ecology. At the highest stage of this concept, it purposes to reduce the waste until toward to ‘‘Zero Waste” and/or ‘‘Zero Landfilling”. In recent years, 3R has received attention from many countries especially in Asia, for example, Japan, China, Republic of Korea, and Vietnam (Sakai et al., 2011).

Amid the awareness of pollution caused by the disposal of industrial waste, the process of selected suitable waste management option must concern both environmental impacts throughout life cycle of waste and economic. The methodologies that assess the environmental impact of alternative options compared with conventional option are inevitable to do. Life Cycle Assessment (LCA) is an extensive and effective tool to assess the environmental aspects and potential impacts associated with a product, process, or service (USEPA, 2012). Nowadays, the LCA are used as a tool for decision making and environmental impact assessment in various applications such as strategic planning, process improvement, product design, and waste management (Nucci et al., 2014; Simões et al., 2013; Valderrama et al., 2013).

Petrochemical plants are typically large and complex, where combination and sequence of processes are usually very specific to the characteristics of the products manufactured. The petrochemical manufactured by cracking, reforming, and other processes cover olefins (including ethylene, propylene, butylenes, and butadiene) and aromatics (including benzene, toluene, and xylenes) made from naphtha and ethane. The base petrochemical products derived from them are converted to a wide range of products including resins and plastics, synthetic fibers, engineering polymers, rubbers, and solvents. In 2008, the Thai petrochemical industry created a value added of 0.5 billion baht. The total capacities for olefins and aromatics were 3.94 and 3.18 million tons, respectively (PTIT, 2009). Nowadays, Thailand is a net exporter in upstream petrochemical, polymer and plastic products, China and ASEAN are the biggest importer with more than 40% of major polymers. The Thai government is currently in “the 3rd wave” of its development plan for petrochemical growth during 2004 to 2018 by increasingly focusing on competitiveness, asset integration and strategic alliances for the industry growth and added value (PTIT, 2009). The development of industrial activities has induced an increase of natural resource depletion and of several pollutant emissions. Fugitive air emissions and wastewaters are of greatest concern. Such plants also generate solid wastes and sludge, which may be considered hazardous because of the presence of toxic organics and heavy metals (MIGA, 2000).

In petrochemical industry, the management of petrochemical waste is not easy because of the presence of different types of wastes and pollutants (Mokhtarani, 2006). Landfill is a conventional method for disposal of petrochemical wastes in Thailand. Unfortunately, landfill sites are often found that they are not well engineered which resulting in the increasing of environmental burden and public health concerns (Chaya and Gheewala, 2007; Menikpura et al., 2012). Therefore, it is important to recognize that landfill wastes should be revived and diverted into recycling stream. In previous works, there have been shown the efficiency of sustainable waste management through many case studies (Dong et al., 2013; Zamorano et al., 2011). However, on the whole, current studies had no involved with petrochemical industry. It seems that the sustainable waste management in petrochemical industry has been neglected as it could be applied to the concept of waste management.

This research, therefore, aims to present the examples of firms that have been driven by vision or by anticipations in advance of regulatory pressures. The theme of the result in this research show how organization are going, or tries to go beyond current environmental standards to create more solid achievements in environmental performance by using 3R concept. Case studies provide other firms, organizations and policy-makers with innovative approach of environmental management that need to study for environmental improvement in petrochemical factory. After 3R concept was applied, Life Cycle Assessment (LCA) is used to assess environmental impact. Finally, the strategy to improve industrial solid waste management system will be proposed. This strategy could be used as guideline for the company that inspired to improve their waste management system.

1.2 Objectives

The main objective of this study is to improve the industrial solid waste management system of the petrochemical complex in Thailand by adopting 3R practices to achieve zero waste to landfill and to move such industry to be green industry. The sub-objectives are consisting of:

1. To study current waste generation rate and waste management practices for petrochemical complex in Thailand.
2. To propose the possibility 3Rs practices for industrial solid waste management in petrochemical complex to achieve zero waste to landfills.
3. To determine the most environmentally friendly options of solid waste management system for petrochemical complex by using the life cycle assessment (LCA) methodology.
4. To develop waste management system of Thai petrochemical complex and move to a more resource-efficient and sustainable future.

1.3 Hypothesis

- The strategy of 3Rs could be applied to petrochemical complex to achieve zero waste to landfills.
- The integrated industrial solid waste management scenario, combining different improvement 3Rs options, could achieve GHG reduction potential.
- Petrochemical complex could develop industrial solid waste management system for toward sustainable waste management.

1.4 Scope of the research

This research aims to develop industrial solid waste management system of the Thai Petrochemical Complex through 3Rs concept. Scopes of this study are:

1. Six petrochemical plants were selected as a case study. The petrochemical case study plants located at the Map Ta Phut Industrial Estate in Rayong province, Thailand. For upstream petrochemical case study, three case study plants use ethane and naphtha as feedstock to produce olefin products. These products attain to use as feedstock in downstream petrochemical case study plants which produce high density polyethylene (HDPE), low density polyethylene (LDPE), and linear low density polyethylene (LLDPE), as shown in Figure 1.

2. The primary data collected from the survey is consisting of quantity of waste, type of waste, source of waste generation, and waste management data.

3. The proposed 3R options and alternative waste management options are focused on only industrial waste disposed of in a landfill. Source reduction is determined as first priority, followed by reusing/recycling, energy recovery and other recovery processes.

4. Life cycle assessment (LCA) methodology is used to determine the suitable industrial solid waste management option by evaluating the current and possible 3Rs options. Selected pollutants in this study were based on laboratory results in which they affect in nine impacts such as: the impact of Global Warming Potential (GWP), Acidification Potential (AP), Respiratory Inorganic (RI), Terrestrial Acidification and Nitrification (TAN), Aquatic Eutrophication Potential (AEP), Aquatic Ecotoxicity (AE), Terrestrial Ecotoxicity (TE), Non-Carcinogenic Effects, and Carcinogenic Effects. The environmental impact in each 3R option was calculated by using IMPACT 2002+ method.

5. Waste management options are investigated both the environmental impact and economic aspect.

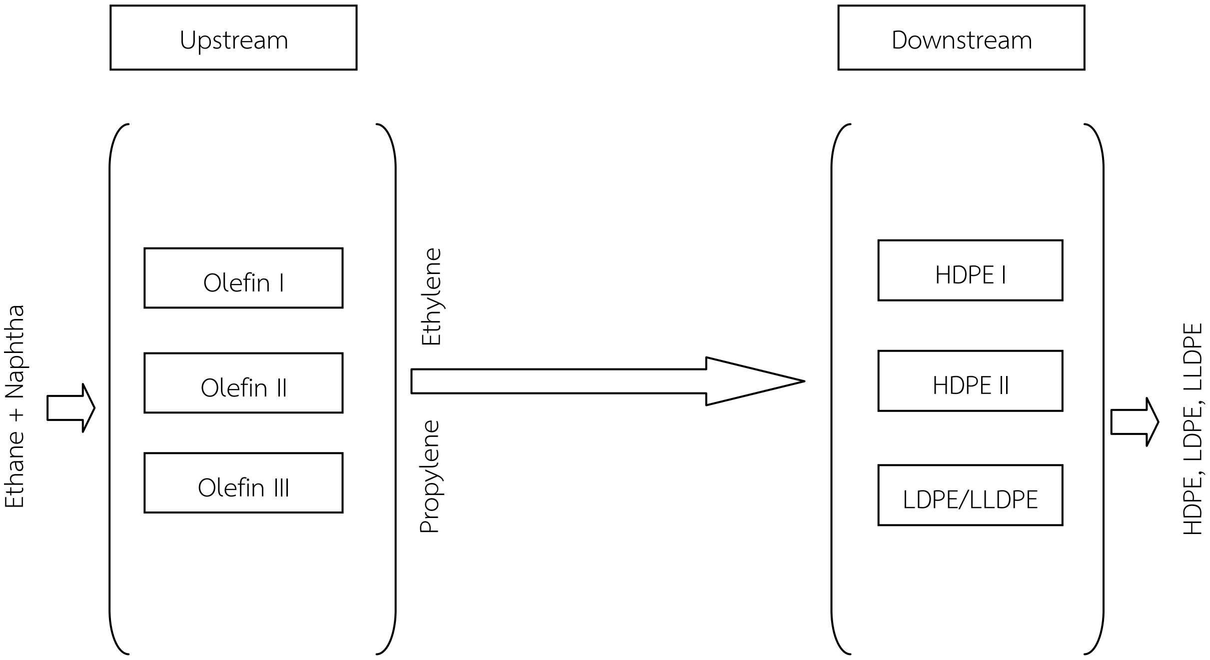


Figure 1.1 Petrochemical complex case study plants

1.5 Thesis outline

The thesis is consisted of eight chapters. Chapter 1 describes the motivation and identifies the problem of this research. The objectives, hypothesis, and scope of the research are also contained in this chapter.

Chapter 2 studies on the status of industrial waste management in Thailand. The problem and recommendation are identified in this chapter. In addition, Chapter 2 provides the literature review on 3R strategy and waste management in petrochemical industry; furthermore, the characteristic of petrochemical waste is also described briefly in this chapter.

Chapter 3 describes about research methodology which divided into three main parts, such as literature review and data gathering, 3R approaches methodology, and environmental impact analysis.

In chapter 4, our viewpoint on the use of 3R concept for petrochemical complex is given and discussed by applying with the olefin plant as a case study. This chapter will include field survey, waste classification, and proposed 3R practices. Discussions focus on development of industrial waste management and possible 3R options to apply with the case study plants. Conceptual model of 3R practices will be created to give an example for other factories. This chapter has been accepted to publish in Waste Management & Research 2014; as doi: 10.1177/0734242X14533604.

In chapter 5, the framework of 3R concept will be created and apply with another case study which is the HDPE plant. The result of chapter 5 demonstrates that the possible 3R options are based on a unique waste characteristic in each case study plant. This chapter has been published in Journal of Material Cycles and Waste Management 16(2), pp.373-383.

Chapter 6 analyses the environmental impact in different disposal scenarios of petrochemical wastes. This chapter will show the comparison of environmental impact between the conventional disposal option (landfill) and the selected 3R option. The result is expected to use as a tool for helping waste manager to select the suitable option.

Chapter 7, the 3R indicator was created to evaluate the performance of 3R options. This indicator will be used to compare the performance of the factories which operated 3R project.

Chapter 8 presents the conclusions and recommendations. Based on the results those obtained from the previous chapters, the 3R strategy is proposed in this chapter and the overall conclusions are presented. Finally, the recommendations for future studies are illustrated.

CHAPTER II

THEORY AND LITERATURE REVIEWS

2.1 Industrial solid waste management system in Thailand: status, problem, and challenge

2.1.1 The laws and regulations

In Thailand, laws used for regulating industrial waste are Factory Act 1992, Hazardous Substance Act 1992, and Industrial Estates Act 1992. The 1992 Factory Act has regulated waste generator and waste processor, while the 1992 Hazardous Substance Act has regulated waste transporter. The 1992 Factory Act empowers Ministry of Industry (MOI) and Industrial Estate Authority of Thailand (IEAT) to set up and enforce the criteria and standards for controlling industrial waste management (PCD, 2012). The legal framework regulates the Thai's industrial waste management system is shown in Figure 2.1.

The wave of waste management legislation continued throughout the next decade. The Factory Law was significantly amended in 2002 through the enactment of The 2005 Notification of MOI which required waste generator must either handle the clean-up of their wastes or hire a waste contractor to eliminate their industrial wastes, furthermore, also required waste transporter and waste processor must operate according to this law (DIWs, 2011). Table 2.1 shows the waste management actor according to Factory Act 1992 and The Hazardous Substance Act 1992.

Table 2.1 Responsibility of waste management actors according to Factory Act 1992 and The Hazardous Substance Act 1992 (IWMB, 2011)

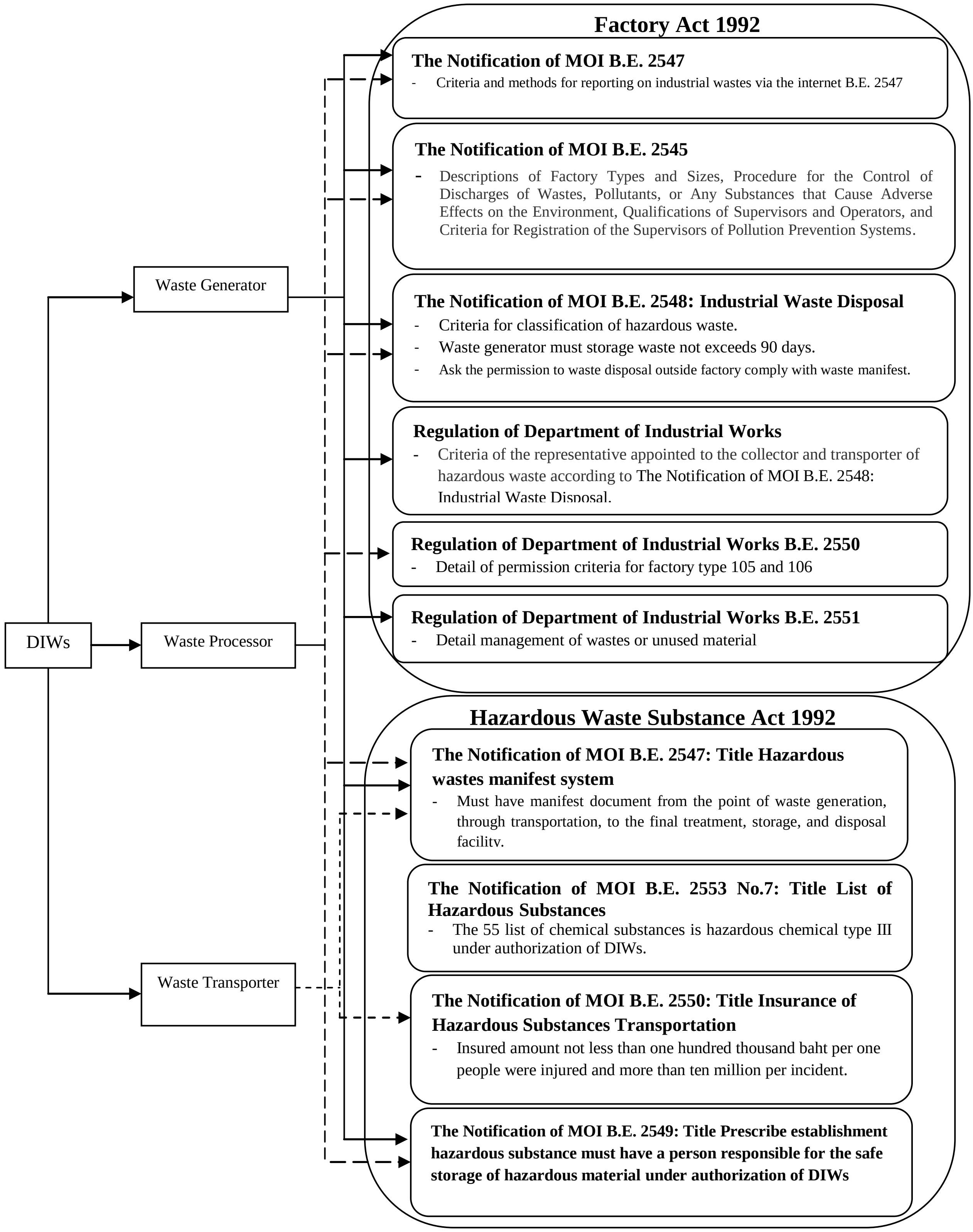
Responsibility	Waste generator	Waste transporter	Waste processor
Requests for permission to store the waste beyond 90 days.	×	-	-

Responsibility	**Waste generator**	**Waste transporter**	**Waste processor**
Requests for permission to take the waste outside factory	×	-	-
Hazardous waste manifest	×	×	×
Inform waste transport	×	-	×
Have a person who responsible environmental protection	×	-	×
Emergency planning program	×	-	×
Liability	×	-	-
Liability waste transportation	×*	×	×*
Keeping result of analysis waste in 3 years	-	-	×
Send annual report	×	×	×

Noted: × refer to the operator must perform the steps above.

* refer to either Waste Generator or Waste processor has appointed waste transporter by themselves

The Hazardous Substance Act 1992 regulated both hazardous and infectious wastes, it permit to handling, storage, transport, and disposal of hazardous waste in according to be specified in a ministerial regulation (PCD, 2012). This law has an important role for waste management in Thailand because it is responsible for supervising waste transportation from waste generator to waste processor.



Factory Act 1992

The Notification of MOI B.E. 2547
- Criteria and methods for reporting on industrial wastes via the internet B.E. 2547

The Notification of MOI B.E. 2545
- Descriptions of Factory Types and Sizes, Procedure for the Control of Discharges of Wastes, Pollutants, or Any Substances that Cause Adverse Effects on the Environment, Qualifications of Supervisors and Operators, and Criteria for Registration of the Supervisors of Pollution Prevention Systems.

The Notification of MOI B.E. 2548: Industrial Waste Disposal
- Criteria for classification of hazardous waste.
- Waste generator must storage waste not exceeds 90 days.
- Ask the permission to waste disposal outside factory comply with waste manifest.

Regulation of Department of Industrial Works
- Criteria of the representative appointed to the collector and transporter of hazardous waste according to The Notification of MOI B.E. 2548: Industrial Waste Disposal.

Regulation of Department of Industrial Works B.E. 2550
- Detail of permission criteria for factory type 105 and 106

Regulation of Department of Industrial Works B.E. 2551
- Detail management of wastes or unused material

Hazardous Waste Substance Act 1992

The Notification of MOI B.E. 2547: Title Hazardous wastes manifest system
- Must have manifest document from the point of waste generation, through transportation, to the final treatment, storage, and disposal facility.

The Notification of MOI B.E. 2553 No.7: Title List of Hazardous Substances
- The 55 list of chemical substances is hazardous chemical type III under authorization of DIWs.

The Notification of MOI B.E. 2550: Title Insurance of Hazardous Substances Transportation
- Insured amount not less than one hundred thousand baht per one people were injured and more than ten million per incident.

The Notification of MOI B.E. 2549: Title Prescribe establishment hazardous substance must have a person responsible for the safe storage of hazardous material under authorization of DIWs

Figure 2.1 The legal framework of regulating the industrial waste management in Thailand (IWMB, 2011)

2.1.2 Regulation agency

Thailand has a number of different agencies regulating different aspects of industrial waste management under a variety of laws either direct or indirect (Katherine and Thomas, 2012). At national level, the strategy and policy of waste management have operated by the following organization:

Direct control

- **The Department of Industrial Works (DIWs)** within the MOI has regulated the entire production process of the factory including environment and safety according to the Factory Act 1992. DIWs is divided into 20 units. The agency responsible for waste management is Industrial Waste Management Bureau (IWMB). IWMB is directly responsible for planning and creating the project related with industrial waste, waste inspection, and the issuance of license under the Factory Act 1992 for waste management facilities. IWMB has responsible for overseeing the storage, transportation, treatment and disposal of industrial waste in Thailand. The process of disposal industrial waste is shown in Figure 2.2. First, waste generator must have a permission document (waste manifest) for disposing waste outside the factory which was send to DIWs via internet. Then, waste transporter, who has the operating license for waste transportation, transport waste from waste generator to waste processor. Waste processor, who received that waste, must send the document to DIWs to confirm the amount of waste for recycling or disposal. In case of the factory located in industrial estates area, waste generator must also send the document to IEAT under Industrial Estate Authority of Thailand Act 1979.
- **The Industrial Estates Authority of Thailand (IEAT)** is established under the Industrial Estate Authority of Thailand Act 1979. IEAT is an

independent agency under the MOI, which regulates the factory where located in industrial estates area.

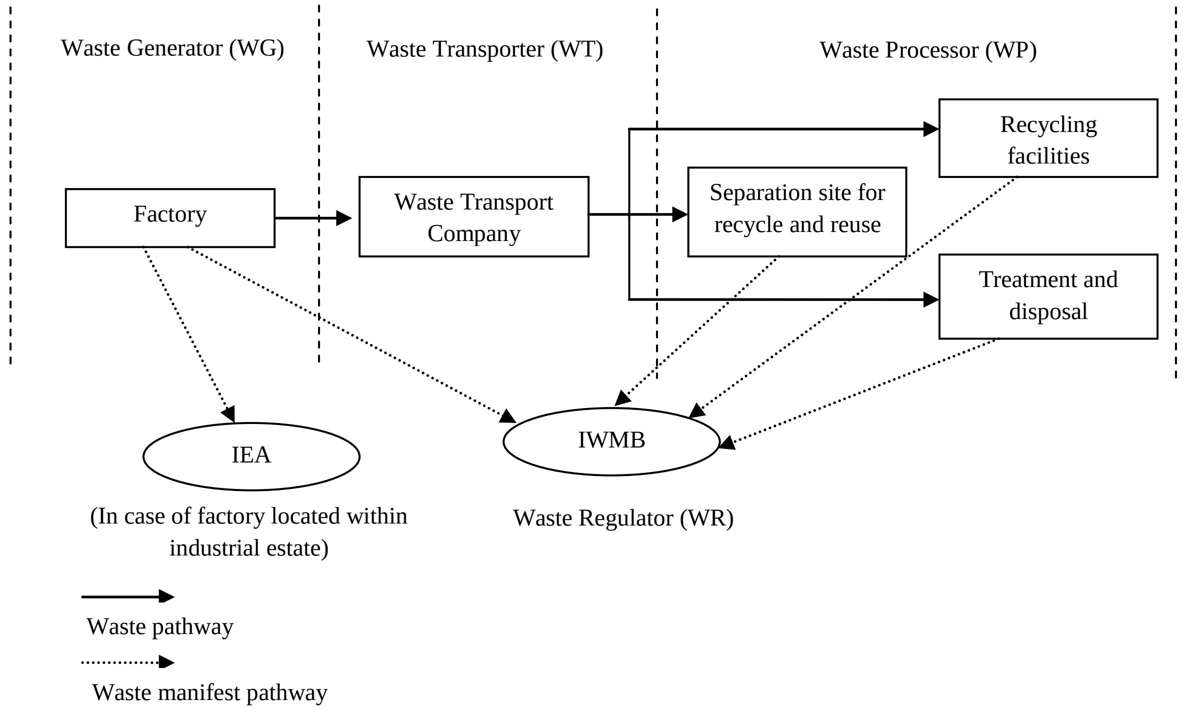


Figure 2.2 Industrial waste management system in Thailand

Indirect control

- **The National Environmental Board (NEB)** has responsible for coordinating environmental policy and planning between government agencies. The main responsibility of NEB is to (i) prepare and plan for conservation and development environment's policies and management of natural resources and the environment in the whole of the country; (ii) coordinate environmental policy and planning between government agencies; (iii) analyze and propose legislative measures, economic measures, social measures, and other measures for promoting the implementation of planning and policies into practice (more information see in http://www.onep.go.th).

- **The Pollution Control Department (PCD)** under the Ministry of Science, Technology, and Environment was established by the Enhancement and Conservation of National Environmental Act1992. The duty of this organization is to develop policy and plan for preserving the national environment, creating quality standards, controlling pollution at sources, and monitoring environmental quality.
- Other agencies who involved with the waste management system such as the Ministry of Public Health and the Ministry of Agriculture and Cooperatives.

2.1.3 Structure of waste management facility in Thailand

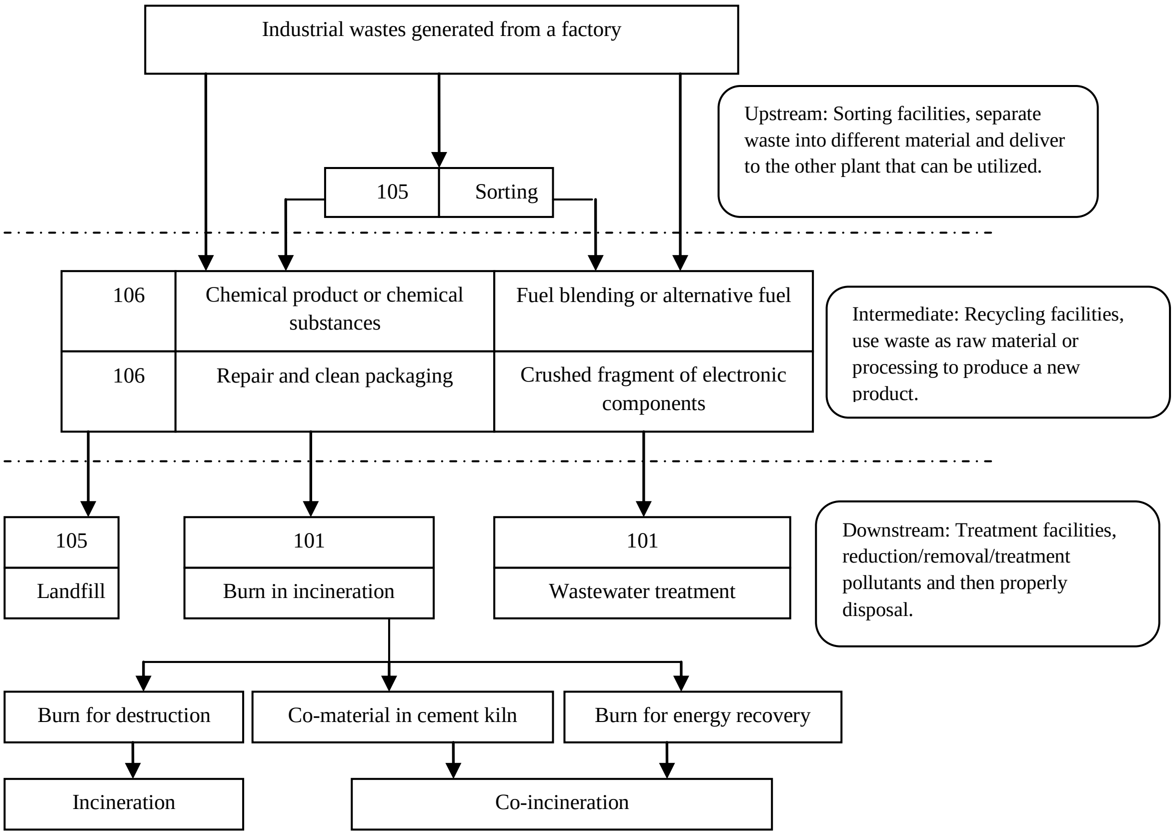
Waste management facility in Thailand can be divided into three sections: upstream, intermediate, and downstream as shown in Figure 2.3 (DIWs, 2011).

1) Upstream waste management facility

This facility is a waste separation plant by using human or machine to segregate waste into different materials (DIWs code 105). The re-useable materials are delivered to the recycling plants which can utilize those wastes, for example, paper mills, recycling plastic factory, and metal casting factory. The waste residue from separation process will be sent to treatment or disposal facilities. From the collected data, there were 468 factories of upstream waste management facilities in Thailand which were located in Central region (227 plants, 48.50%), Eastern region (192 plants, 41.02%), Northern region (26 plants, 5.56%), Northeast region (11 plants, 2.35%), Western region (9 plants, 1.92%), and Southern region (3 plants, 0.64%), respectively. Obviously, most of the upstream waste management facilities were located in Central region and Eastern regions because in that area there is a site of many industrial estates which generated a lot of industrial waste.

2) Intermediate waste management facility (DIWs code 106)

This facility is the factory that used waste as raw material to produce a new product such as: fuel blending or fuel substitution; chemical product; repaired and cleaned-up packaging; and grinding electronic equipment. This section is playing an important role for recycling stream of industrial waste. The capacity of recycling and disposal industrial waste is shown in Table 2.2. The number of factories those registered for recycling hazardous waste is highest. It has 196 factories throughout the country but its capacity to recycling is only 0.61 million ton/year (DIWs, 2008). This can be implied that most of the waste recycling companies in Thailand are small and medium sized company (SMEs). In a group of recycling hazardous waste business, the type of recycling factories (used oil, solvent, fuel mixing, and fuel substitution) have the highest capability to accommodate the waste volume up to about 480,000 tons/year, while the precious metals extraction has the lowest capability to accommodate the volume of waste, only about 1,600 tons/year (DIWs, 2009). For recycling non-hazardous waste business, the group of waste compaction factory (i.e. paper, plastic, and metal/non-metal) has a highest capacity to handle the wastes, followed by the group of recycling plastic factory which was distributed in every region. Meanwhile, the group of composting factory has the capacity to accommodate the volume of waste was minimal, only about 300 tons/year (DIWs, 2009).



Source: Adapted from (DIWs, 2011).

Figure 2.3 Structure of industrial waste management facilities in Thailand

Table 2.2 Capacity of recycling and disposal industrial waste.

Type of waste management facilities	Hazardous waste		Non-hazardous waste	
	Number of factory	Capacity (million ton/year)	Number of factory	Capacity (million ton/year)
Burn in incinerator	10	8.82	5	8.85
Landfill	4	0.92	8	0.51
Recycling	196	0.61	204	0.44
Total	210	10.35	217	9.8

Source: (DIWs, 2008)

3) Downstream waste management facility (DIWs code 101, 105)

This facility is the treatment of industrial solid waste or wastewater by using physical, biological, and chemical methods (DIWs code 101), and includes disposal in a landfill sites (DIWs code 105). The type of downstream waste management facilities can be separated as follows:

(1) Burn in incinerator (DIWs code 101)

Incineration can help to reduce the volume of waste and transform waste to ash, air pollution, dust, and heat. All incinerators must have temperature, exhaust fumes, and ash control systems. Heat recovery from burning waste can be used to produce electricity. By the way, most of incinerators emit toxic pollutants in form heavy metal such as vanadium, manganese, chromium, nickel, arsenic, mercury, lead and cadmium. It could also occur in form of heavy ash and fly ash which must be disposed of in a secure landfill. As shown in Figure 2.3, type of incinerator in Thailand can be divided into 3 types such as: (1) burn for destruction; (2) co-material in cement kiln; (3) burn for energy recovery. In Thailand, the capacity of burning hazardous waste was 8.82 million tons/year by 10 furnaces across the country, which largely destroyed as co-material in cement kiln. For incinerator that specified for destructing industrial hazardous waste, Thailand has only one facility where located in SamutPrakan province. Table 2.3 shows the condition of incinerator operation in Thailand (Punsuwannakhi, 2012).

Table 2.3 Condition and efficiency of cement kiln and incinerator in Thailand

Type of kiln	Temperature (°C)	Residence time (sec)	Efficiency of destruction (%)
Cement kiln	1400-2000	10-15	99.99
Incinerator	850-1200	2-5	99

Source: (Punsuwannakhi, 2012).

(2) Wastewater treatment (DIWs code 101)

The process of wastewater treatment plant is to reduce/eliminate/treat the pollutant that contained in the wastewater, and also included properly disposal of sludge from wastewater treatment plant. Techniques of treatment wastewater can be divided into two main methodologies such as: physical and chemical treatment processes, and biological processes. Physical and chemical treatment processes are the process to reduce the toxicity of waste by changing hazardous substances in the form of sludge, insoluble salt compounds, or neutral solid compounds. Biological treatment process is included both aerobic and anaerobic bacteria to degrade the organic compound. However, it is well known that this process could not apply to treat hazardous waste due to hazardous pollutants inhibit the bacteria growth.

(3) Landfill (DIWs code 105)

In Thailand, landfill can be divided into two categories, such as sanitary landfill and secure landfill. Sanitary landfills are applying with non-hazardous waste. Secure landfills are used for hazardous waste. Thailand had been existing three secure landfills with a total capacity of 635,000 tons/year (UNEP, 2012). In present, however, there is only one secure landfill site that still operate in Thailand. Table 2.4 shows the number of landfill sites throughout Thailand. It can be observed that Eastern Region has highest number of landfill sites (11 sites), followed by Western Region (4 sites), Northern Region (3 sites), and not appear in the Southern Region. All landfill sites in the Eastern Region were available for non-hazardous waste, although in that area is a large source of hazardous waste generation from petrochemical, chemical, and non-ferrous industries.

Table 2.4 Number of landfill site throughout Thailand.

Region	Province	Type of waste	Number of business
Central	Saraburi	Non-hazardous and Hazardous waste	1
Eastern	Chonburi	Non-hazardous waste	2
	Rayong	Hazardous waste	1
		Coal ash landfill	1
		Separated sludge to landfill	2
	Chachoengsao	Non-hazardous waste	1
	Prachinburi	Non-hazardous waste	3
	Sa Kaeo	Non-hazardous waste	1

Region	Province	Type of waste	Number of business
Central	Saraburi	Non-hazardous and Hazardous waste	1
Northern	Chiang Mai	Non-hazardous waste	1
	Lampang	Non-hazardous waste	1
	Phetchabun	Non-hazardous waste	1
Western	Ratchaburi	Non-hazardous waste	2
		Non-hazardous and Hazardous waste	1
	Kanchanaburi	Non-hazardous waste	1
		Total	19

Source: List of landfill plants that are allowed to operate by Department of Industrial Works (DIWs), 2006. http://www2.diw.go.th/iwmb/customer.asp. Better World Green Public Company Limited, 2008. http://www.betterworldgreen.com/www/th/about_profile.php

2.1.4 Challenging and opportunities for improving Thai waste management

- The current situation of illegally dumped waste in Thailand has increasing dramatically. The one reason is generated from the penalty is not as hard as they should. The illegally dumped waste is punishable by fines only 200,000 baht, while the license revocation is not effective in practice. Therefore, it should be increased the fines, and defined illegal dumping waste is a criminal to have more severe penalties. Moreover, the persons who illegally dumped waste must have the responsibility on the restoration of environmental damage that occurs all.
- Officials or agencies related to waste management system should give the education and information about waste management system to entrepreneurs because the validation process of the past is attend to an order to operator only, but not recommendation.
- Industrial waste management system in Thailand was mainly 'top-down' in approach, it should be changed into 'bottom up' approach by more encouragement and environmental stewardship rather than command and control.

- Waste exchange, 3R concept, and Industrial Ecology concept should be recommended by an incentive policy approach to the stakeholder who participant with waste management system.

From the data collected in this section, it can be concluded that industrial waste management system is a very important mechanism to support the development of industry and communities. Nevertheless, the incidents of illegal dumping of waste in Thailand have occurred over and over again, which resulted in reinforced society mistrust, and stimulated resistance from communities in industrial areas. With the recommendation in this section, it was expected to be used as an idea to relieve the problem of industrial waste management in Thailand.

2.2 Environmental Management Concept

2.2.1 End-of-pipe treatment

End-of-pipe treatment was used as a tool in the first stage of environmental management in Thailand; which the government efforts to establish environmental standards and regulation also known as command and control. Since 1969, command and control approach was used for pollution control in Thailand. Standards were set up to control the quality of pollutant before discharge to the environment. The quality of emitted pollutants must comply with standards (command); and the standards can enforce the polluters by using fine and/or penalty in case of the polluter neglect (control) (Chavalparit et al., 2006; Kaosa-ard et al., 2008). Command and control regulation has successful for environmental prevention from point sources; it can design based on engineering approach to specific characteristic of pollution that according with the environmental law (Stuart, 2006). However, this approach has shown some weak point such as; polluters can pollute independently on condition that comply with standards because they have not incentive to reducing their pollution; pollution control authorities lack the technical expert and manpower to detect compliance with the law; and there is no motivation to pay serious attention with theirs pollutant discharge because the fines and penalty are too low.

To comply with the law that set up the standards of pollutant, polluter must install end-of-pipe pollution control and waste clean-up technologies. Nowadays, end-of-pipe pollution control plays an important role for reducing toxicity and volume of industrial waste before discharge to the environment. End-of-pipe technologies have been developed every year to increase the efficiency of waste disposal. Various treatment plants, for example, biological treatment, physical treatment, physico-chemical treatment, chemical treatment, chemical stabilization, and etc., apply to treat pollutants depending on the characteristics of industrial wastewater, solid wastes, and air pollutants. Nonetheless, only with installation end-of-pipe technologies cannot comply with intensive regulation because technology is not enough advance and high operation cost for treating wastes. Consequently, this concept does not resolve at the original cause, but it creates the additional cost for production process and not sustainable.

2.2.2 Cleaner Production (CP)

In the mid-1980s, the concepts of cleaner production were introduced by United Nations Environment Program (UNEP). Cleaner production is a strategy to improve products and processes, which based on conserving material, efficient energy, minimizing waste, producing ecologically product, reducing potential risk to humans. It can help to reduce both environmental impact and cost of production, moreover, reform negative images of polluting industrial process to positive images of technologies. Van berkel (2010) stated that the variety of practices lead to succeed cleaner production concept, for instance, good housekeeping, process or equipment modification, changing raw material, on-site reuse and recycling, and changing technologies (Van Berkel, 2010).

Amid with increasing of environmental pollution concerns, cleaner production has shown potential benefits for environmental management. It as a set of tools, as a strategy, and as a way of thinking (Fore and Mbohwa, 2010; UNEP, 2001). While the pollution control authorities' attention is focus on pollutant discharge between the factory boundaries and the public environment, cleaner production determine about inside the production process until send to the customer; in addition, the results of applying concept create a new approach for environmental management, for example, eco-design, life cycle assessments, Extended Producer Responsibility initiatives (UNEP, 2001). The cleaner production process is shown in Figure 2.4. Cleaner production is a subset of the concept sustainable development as well as other tools (ex. pollution prevention, clean technology, waste minimization, and etc.); it has a benefit in both an industry and environment that is the highlight of sustainable development. Although cleaner production and clean technology have a similar concept, there are some differences in a definition. Cleaner production emphasizes on the product rather than the function; therefore, it need to assess the whole life cycle (Roland, 1995). Zhou (2009) was claimed about the different between cleaner production and ISO 14000; cleaner production concentrates on the product, while ISO 14000 concentrate on governance and environmental management standards (Zhou et al., 2009).

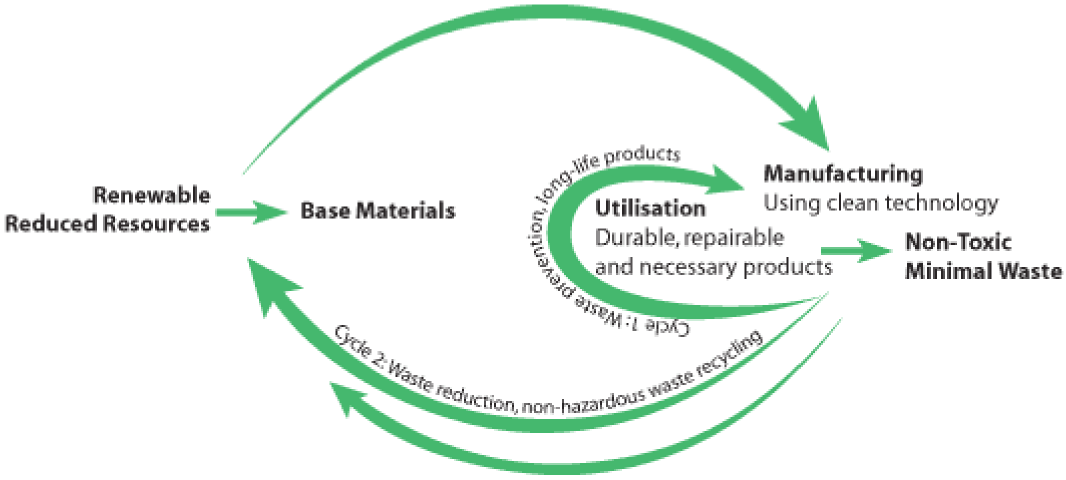


Figure 2.4 Cleaner production process (Clean production action, 2011)

2.2.3 Industrial Ecology (IE)

Industrial Ecology (IE) concept has been developed in last twenty years (Roberts, 2004). This concept is an attempt to introduce a new framework for consideration the impacts of industrial systems to natural ecological systems, including physical, chemical, and biological interactions between industrial and ecological systems. The ultimate goal of this concept is toward to sustainable development. Industrial ecology attends to apply the natural system with the industry. The main point of industrial ecology is about ways to join different wastes from different plants into operating system for minimizing the total amount of industrial wastes to disposal. In addition, this concept is focus on improving the flow of materials and energy to closed loop system to reduce material and energy losses. Gibbs stated that the key concept of industrial ecology is the circular systems or close loop system rather than composed of isolated components in a system of linear flows (Gibbs and Deutz, 2005). The industrial ecology consists of five important concepts is as follows (Garner and Keoleian, 1995):

- System analysis
- Material and energy flows and transformations
- Multidisciplinary approach
- Analogies to natural

- Linear versus cyclical loop systems

With the ideal perspective of industrial ecology, only solar energy coming from outside the boundary, while wastes or by-product is reusing, recycling, and recovering within boundary of industrial ecology.

Industrial ecology can apply in both macro and micro levels. Macro scale application is often associated with the project planning, the project design, the policy framework conductive to the ecosystem for large industrial, for example, global industrial ecosystem, regional industrial ecosystem, and so on. In case of micro scale, it means that applied this concept with the enterprise group, the organization or the community.

2.2.4 3R's Concept

Amid the ongoing development to improve quality of life of the country's population, it resulted in generating a lot of waste which impact to the environment. In 2011, our world is facing on depletion of resources and environment and waste increasing, although we are made aware of this problem for a long time. To deal with the waste, the one important concept in the adoption of waste management is the hierarchy of waste management also known as the 3R's concept (as shown in Figure 2.5). The concept of "3R's" means reduce, reuse and recycling products or resources, furthermore, imply on increase recycling rate by using recyclable material; reusing products, resources, and discarded material including reducing energy consumption (UNEP, 2004). 3R's concept emphasizes priority to reduce, re-use, and recycle for toward to the concept of zero waste in finally (Diaz, 2011). At the policy level, 3Rs is an environmental policy concept that represents the concept of balancing environmental conservation and economic growth through the effective use of resources (MOE, 2008).

3R's strategy is a new concept to cope with the increasing quantities of waste in addition to the existing concept like clean technology, clean production, and industrial ecology; it has been received attention from many countries. At regional level, G8 leaders was signature on international cooperation at the G8 Sea Island Summit for disseminating and sharing among Asian countries the best practice, tools and technologies on various aspects of the 3R's. At global level, The Chairs Summary of 18th Session of the Commission on Sustainable Development (CSD-18) in 2010 concluded that "Regional initiatives promoting 3Rs, such as the 3R's Forum in Asia, should be enhanced"; the key message after CSD-18 meeting is implying that we should expand the information and stimulate the exchange the knowledge of waste minimization and limitation movement of waste; for example, resource prevention and waste minimization should be considered as first priority to guide action on waste for toward to zero waste economy, and waste management needs to be addressed through integrated approaches. The basis for sustainable waste management consists of reducing waste production, recycling waste and reusing material; in addition, extended producer responsibility should be applied as accessory equipment of 3Rs concept (CSD-18, 2010).

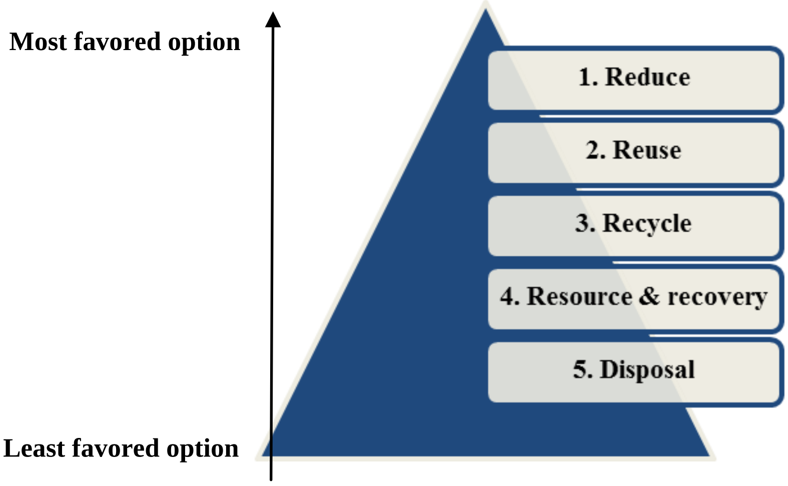


Figure 2.5 Waste management hierarchies

The hierarchy of waste management or 3Rs concept can be demonstrated step by step as follows:

Reduce

Reducing waste in manufacturing plant can lead to savings in the raw material usage and reduction in waste generation as well. Industrial are often seen that the reduction means only reduction amount of waste sent to landfill, but in reality it refers to any kind of activities that generate waste. Develop practice, process, or good housekeeping is also source reduction including chemical substitution, process modification, and improving operating procedures.

Reuse

Reuse would be applied after the reductions of waste have been exhausted. The concept of reuse refers to the reuse of its original state either in the same manner for which it was designed or in a new manner but without any physical or chemical modifications. This manner is resulted in substantial saving. In some cases, however, reuse options have constraint due to related with public health and sanitation. The application of this concept has obviously important in reduction of raw material, employment, and amount of waste in a landfill or an incineration. For enhanced effective in reuse strategy, it need to observe and care in the reuse of certain items due to related with public health, sanitation, durability, and performance guarantees.

Recycling

Recycling is available option after reduction and reuse cannot be applied. Recycling refers to discarded materials which are recovery and processes either physically or chemically in order to convert as a new product. Recycling processes are the most widely treatment method use in industrialized countries and developing country, however, most of the recycling technologies in developing countries are low-technology and not have potential like developed countries. Waste management in developing countries (e.g. Thailand) is consisting of storage, collection, and final disposal. Some stages have operated by informal sectors; for example, zaleng or scavenger plays an important role for storage and collection by travel on the street to purchase or collect some discarded materials those can sell to recycling plant.

As shown in the previous section, the sustainable waste management was consisted of various concepts. The comparison of advantage and disadvantage in each option can be demonstrated in Table 2.5. In this study, however, we prefer to select 3R concept to apply for improving waste management system in petrochemical industry because its characteristic is easy to apply at the enterprise level and easy for the people responsible for waste management at the factory to understand. It is an effective tool to implement in a microstructure (single object) to manage increasing quantities of waste. This concept is aimed at reducing the waste to ‘‘zero waste” and/or ‘‘zero landfilling”. In recent years, 3R has received attention from many countries, particularly in Asia, including, Japan, China, the Republic of Korea, and Vietnam (Sakai et al., 2011).

Table 2.5 Comparison advantage and disadvantage tool for sustainable development

Tools	Advantage	Disadvantage	Scale of co-operation
End of pipe technology	• Reducing toxicity and volume of industrial waste before discharge to environment according to the law and regulation	• Costly for operation • The concept does not resolve at the original cause, it creates the additional cost for production process and not sustainable	Individual firm
Cleaner production (CP)	• Improving products and process continuously based on material conserving, energy efficient, waste minimization, produce ecologically product • Reduce the potential risk to humans which can help both environment and reduce costs of production simultaneously	• Inefficiency enforcement and regulate firm • Lack the basic knowledge of cleaner production and desire to implement cleaner production (in developing country) • Lack of finance incentives and additional economic constraint	Individual firm
Eco-industrial park (EIP)	• Economy of scale • Proximity between supplier of raw materials • Improving the flow of materials and energy to closed loop system for reduce material loss or energy loss and reduce environmental pollution simultaneously • Land use and water resources to maximum benefit and minimal environmental impact	• Difficult to find the firm that related in terms of materials and energy • Investors are not sure that investing in eco-industrial park project will have feasible in term economic or not • Innovative ideas are often high risk • The philosophy of the business of firm is not the same and in some cases it may be an incompatibility	Group of firm

Tools	Advantage	Disadvantage	Scale of co-operation
3R's approach	• Improving on recycling rate by using recyclable material; reusing products, resources, and discarded material including reducing raw material and energy consumption • Balancing environmental conservation and economic growth through the effective use of resources	• Lack of truly understanding about 3R's concept and process to implement 3R's option (in developing country) • Lack of advance recycling technology	Individual firm

2.3 Life Cycle Assessment (LCA)

To identify the benefit of proposed 3R option, the methodology of compared environmental impact with conventional option is inevitable to do. Life Cycle Assessment (LCA) is an extensive and effective tool to assess the environmental aspects and potential impacts associated with a product, process, or service (USEPA, 2012). Nowadays, the LCA are used as a tool for decision making and environmental impact assessment in various applications such as strategic planning, process improvement, product design, and waste management (Iraldo et al., 2014; Nucci et al., 2014; Simões et al., 2013; Valderrama et al., 2013). LCA is a favorable tool for evaluating the environmental performance of municipal solid waste (MSW) management systems (Cleary, 2009). In term of waste management, LCA is typically focusing only on the comparison of different waste management options, not include the entire life cycle of the products that transform to wastes (JRC, 2011).

2.3.1 LCA concept (ISO 14040)

Generally, LCA means the methodology of looking at the effect of products (or processes) including packaging on the environment, and determining the whole life cycle (cradle-to-graves) (Varoonchotikul, 2011). The LCA methodology can be divided into four parts as follows:

1) Goal and Scope Definition

The common LCA goal is to conduct an assessment of the environmental attributes of a specific product and process. It will derive the information from the assessment and focus on how to improve environmental performance.

The functional unit means the amount of product, material, or service to which the LCA is applied. The choice of the functional unit is therefore not straightforward. However, when conduct comparative LCA, a fair comparison can be accepted if all system will be compared in the same functional unit.

2) System boundaries

The system boundaries define what products or product families are to be determined and by what means the associated systems are to be defined and described; furthermore, it can define which part of the life cycle or process are considered to the system.

3) Life Cycle Inventory

Life Cycle Inventory (LCI) is resources consumed and environmental emissions calculations by using the product unit consumption rate. LCI is databases that can help LCA practitioners answer questions about environmental impact.

4) Impact Assessment

Impact assessment is a process to create structuring and supporting the development of policies, in addition, identifies the main options for achieving the objective and analyses their likely impacts in the economic, environmental and social fields. Impact assessment can represent the advantages and disadvantages of each option to select the best option for environment.

2.3.2 SimaPro Program

SimaPro is LCA software which has been widely selected for LCA application by industry, research institutes and consultants. The program can model products and systems from life cycle perspective or build complex model in a systematic and transparent way using SimaPro's unique features such as parameters and Monte Carlo analysis. This software contains life cycle inventory databases with a broad international scope and a variety of 17 different impact assessment methods (PRéConsultants, 2013).

2.3.3 LCA on waste management

LCA method is also used to assess environmental impact of waste management, especially for sludge (Aranda-Usón et al., 2012; Cherubini et al., 2009; Hong and Li, 2011; Johansson et al., 2008; Lederer and Rechberger, 2010; Lundin et al., 2004; Mills et al., 2014; Tarantini et al., 2007; Yoshida et al., 2013). As shown in Table 2.6, it has been received widespread attention in recent years through different functional units and assessment methodologies (Hong and Li, 2011; Liu et al., 2011; Suh and Rousseaux, 2002; Vlasopoulos et al., 2006). From the review, it could be indicated that most of the LCA studies concerned on sewage sludge, very few studies on industrial sludge especially in Thailand. It is well known that the different result of LCA study can be happened by different assumption and boundary system. Kiatkittipong et al (2009) has stated that the result of LCA study should be carried out on a case-by-case basis; it means that the original data set of life cycle inventory (LCI) is very important (Kiatkittipong et al., 2009). However, the data of sludge characteristics from wastewater treatment system in Thailand is very rare. For other waste types, LCA on waste management was mainly operated on Municipal solid waste (MSW) or organic wastes, for example, food waste, plastic waste, and etc. However, there are small numbers of researches on LCA applied with petrochemical wastes.

Table 2.6 LCA studies on waste management

Year	Author	Functional unit	Methodologies
2006	N. Vlasopoulos et al.	1000 m3/day of water input	Sima pro 6 / CML 2 baseline 2000 V2.1 / Decision support system by Imperial College
2009	W. Kiatkittipong	1 ton of bagasse	EDIP/UMIP 97 V2
2002	Y-J Suh, P.	1 ton of mixed sludge in dry basis (sewage sludge)	SETAC/CML
2010	J. Lederer et al.	1 ton of raw sludge	CML / IMPACT 2002+
2010	J. Hong et al.	1 ton of dry MSW	IMPACT 2002+
2011	J. Hong and X. Li	1 ton of Portland fly ash cement	IMPACT 2002+
2011	Q. Liu et al.	1 TJ steam	EDIP/UMIP 97 V2.03
2012	Aranda-Uson et al.	1 kg of clinker production	Recipe method
2013	B. Liu et al.	1 dry ton of sludge	IPCC and other emission factor from literature review.
2013	Valderrama et al.	1 kg of clinker production	GWP: IPCC 100 years. CML 2000. Eco-indicator method.

2.4 Petrochemical industry in Thailand

In 2008, the Thai petrochemical industry created a value added of 0.5 billion baht. The total capacities of producing olefins and aromatics were 3.94 and 3.18 million tons, respectively (PTIT, 2009). In the present, Thailand is a net exporter in upstream petrochemical, polymer and plastic products. China and ASEAN are the biggest importer with more than 40% of major polymers. The Thai government is currently in “the 3rd wave” of petrochemical development plan by focusing on competitiveness, asset integration and strategic alliances for the industry growth and added value (PTIT, 2009). Most of the petrochemical industries located at Map Ta Phut Industrial Real Estates (MTPIE). MTPIE contains 31 factories or 58.49 percent of the total number of factories in this group (Charmondusit and Keartpakpraek, 2011). The petrochemical industry can be classified into three main groups, on the basis of their product: upstream, intermediate, and downstream (see in Figure 2.6).

The upstream petrochemical industry use fossil fuel as feedstock (such as naphtha, liquefied petroleum gas, and ethane) to produce seven kinds of products or “the Seven Sister”. The Seven sister is divided into three groups, basis on the molecular structure: alkane group (methane based); olefin group (ethylene-based, propylene-based, and mixed C4 based); and aromatic group (benzene-based, toluene-based, and xylene-based). The products of upstream petrochemical group are used as feedstock for intermediate and downstream petrochemical groups to produce plastics, solvent, synthetic organic, and etc. (DEDE, 2006).

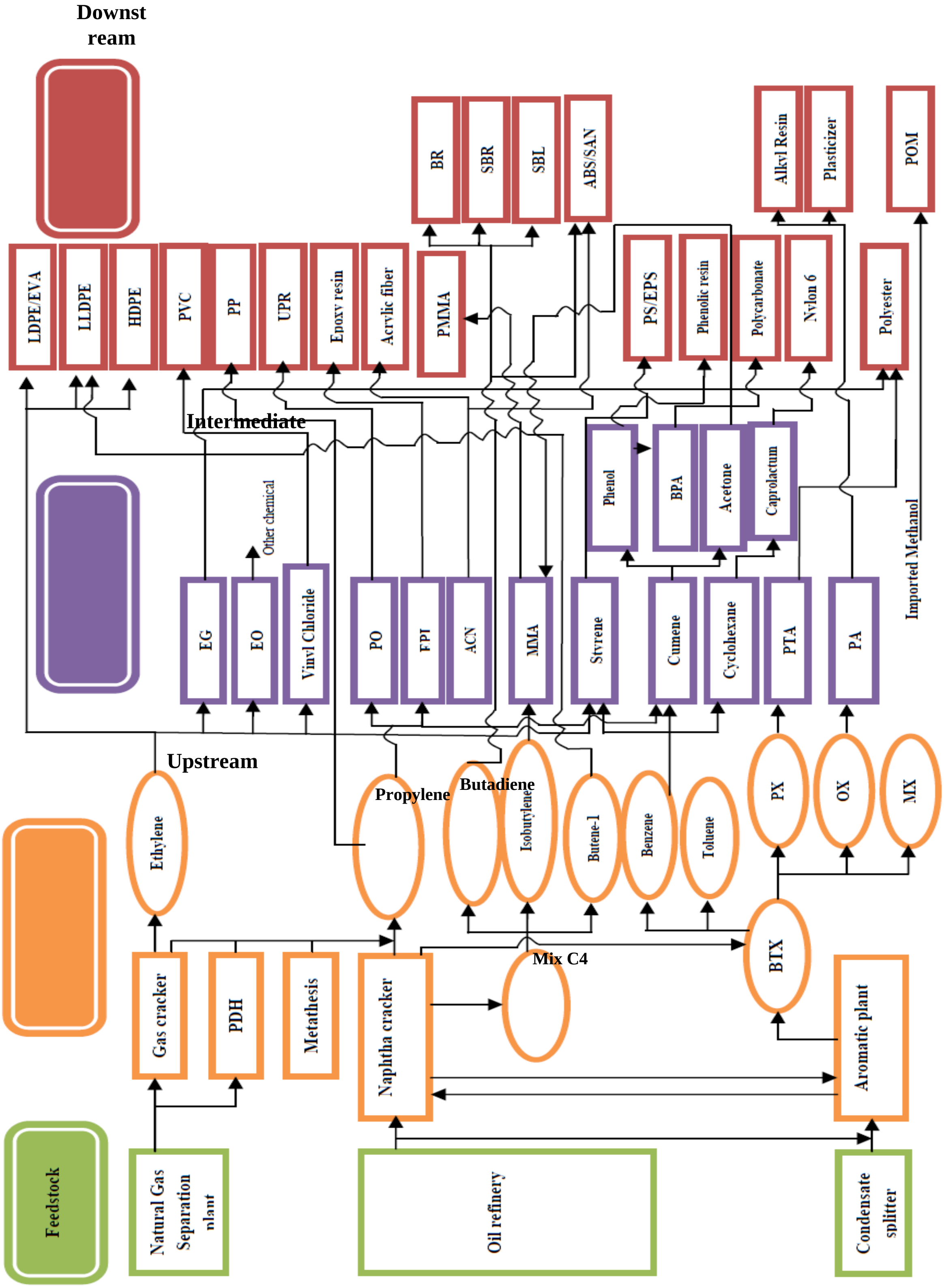


Figure 2.6 Thai Petrochemical Complex Flow (Adapted from (PTIT, 2012))

2.4.1 Petrochemical industry and the environment

A petrochemical factory is typically large and complex, which the combination and sequence of processes are usually very specific based on the characteristics of the product manufactures (IFC, 2007). Prior to be the petrochemical products, raw material will be passing through a multi-step processes, for example, cracking, reforming, distillation, and etc. For those reason, the development of petrochemical industrial activities has induced an increase of natural resource depletion and of several pollutant emissions. Fugitive air emissions and wastewaters are of greatest concern. Such plants also generate industrial solid wastes and sludge, which may be considered hazardous because of the presence of toxic organics and heavy metals (MIGA, 2000).

In the last decade, the pressure of environmental management has been increased because the NGOs and villagers who live near the factory have increased an awareness of the pollutant toxicity which emitted from the industry. Although Thai petrochemical industry has a modern of abatement pollution technology to treat pollutant and meet the standard according to law regulation, it is still not enough to response social concerns around industry location. Therefore, proper environmental management is an emerging issue in Thailand, especially proper waste management, can be considered as a critical issue in the environmental management of Thai petrochemical industry.

2.4.2 Waste generation

In petrochemical industry, solid waste is generated by production process, maintenance program and any activities in plants which are obstructing for development of the petrochemical industry. Wastes generated in the petrochemical plant have various characteristics. It consisted of different types of waste and their pollution; therefore, waste management is difficult and complex (Abduli et al., 2006). The quantities of waste from each waste type vary from year to year in accordance with plant activities, which can make estimations difficult (Alshammari et al., 2008).

Solid wastes generated in petrochemical plant can be divided into three categories based on waste sources such as equipment and packaging wastes, maintenance wastes, and production process wastes. The characteristics of solid wastes generated in petrochemical plant are briefly described below:

(1) Equipment and Packaging wastes

- **Insulation**: petroleum employs various types of insulation, for example, refractory brick, rock wool, foam glass, ceramic wool. Maintenance program and accidental leakage are main cause of insulation waste generation. Some insulation wastes are contaminated with oil and chemical substances which determined as hazardous wastes.
- **Contaminated garbage**: contaminated garbage means the type of waste that contains material contaminated with oil, for example, gloves, tripe, rag, paper, and etc.
- **Contaminated container**: contaminated containers are referring to containers holding residual of hazardous materials at the sites. For instance, catalyst container, chemical reagent container, and used oil container, these wastes are generated every month in petrochemical plants.
- **Packed column**: packed column is used to increase the surface area of mass transfer in the column. This waste is generated when packed column damage or out of services. Packed column can damage due to high pressure and fouling mechanisms. Fouling mechanisms can be created by several of mechanisms such as coking, salt deposition, polymerization, and chemical or physical interaction; in addition, erosion problem of packed column can generate directly from solid particles when contact with vapor stream (Koch-glitsch, 2010).

(2) Production process wastes

- **Caustic and yellow oil**: caustic towers at petrochemical plants were operated to remove acid gases from ethane gas, such as H_2S and CO_2. Spent caustic contains mercaptans and sulfides which are reactive and odorous. This waste requires special treatment before discharge to a wastewater treatment plant (Maugans et al., 2010).
- **Molecular sieve**: molecular sieve is used to remove water in feedstock of petrochemical production. Typically, molecular sieve is a zeolite compound synthesized $((K_2O.Na_2O).Al_2O_3.2SiO_2.xH_2O)$; it can absorb water at cold condition and dehydrate water at hot condition. The advantage of molecular sieve is low energy consumption compared with distillation process. However, molecular sieve has high rate of fouling when their life time is more than five years.
- **Oligomer**: oligomer (or green oil) is a mixture compound between C_4 and small amount of C_6 to C_{20+}; it is generated from fairly rapid catalyst deactivation (Mohundro, 2003).
- **Monoethanolamine (MEA) mixed with water**: MEA is an amine chemical group which used to remove acid gas, such as H_2S and CO_2 (Gary and Handwerk, 1984; Kohl and Nielson, 1997). However, the MEA can be corrosive and difficult to regeneration. Therefore, when operate gas absorber unit, diluted concentration of MEA (about 18% (v/v) of MEA) with water is used instead (Plasynski and Chen, 2000). After finish this operation, the spent of MEA appeared at the bottom of gas absorber unit.
- **Spent catalyst**: the catalyst was used in fluid catalytic cracking unit (FCCU) when naphtha was used as raw material. This operation generates spent catalyst as a solid waste every year.
- **Coke & Tar**: some fractions of naphtha feedstock have consisted of high molecular weight of hydrocarbon and non-volatile components which these components place down as coke in the furnace of cracking unit; meanwhile, other feedstock (kerosenes, gas oils)

generates large quantities of tar which is the cause of coking in the furnace (Mccoy and Stell, 2008).

- **Dimethyl disulphite**: Dimethyl Disulphite (DMDS) is a pale yellow liquid and a pungent odor. It uses as additives for preventing carbon monoxide (CO) occurred during steam cracking process. In addition, DMDS is used decoking operations in petrochemical industry (Dhuyvetter et al., 2001).

(3) Maintenance waste

- **Chemical cleaning waste**: under maintenance program, toxic or flammable gases of raw material are removed by routine operating procedures. However, some types of hydrocarbons or chemicals are difficult to remove, for example, heavy oils, H_2S, FeS, and polymer deposits; they need require special treatment by using chemical oxidation (Ondrey, 2007). After used special chemical solution, this solution became to waste and need to dispose of carefully due to high toxicity.
- **Polymer and waste oil**: at the compressor unit, polymer often adhere on the rotor and other parts of internal compressor which lead to energy losses and mechanical problems (De Haan and Sullivan, 2001). Hence, wash oil and water are used to remove fouling resulted in creating waste polymer and waste oil from the maintenance program.
- **Lube oil/used oil**: lube oil is used to reducing friction and increasing mechanical equipment lifetime. After completion, spent used oil became to waste and need to disposal properly to prevent negative effect to the environment (Charles and 1994).
- **Sand contaminated with oil and chemical**: sand blasting is one of the abrasive methods for cleaning the internal surface of process lines and equipment which can apply for different pipe sizes. Sand was sprayed from the nozzles to clean walls of the pipe (Garverick, 1994).

After that, sand contaminated with oil and chemicals was generated as hazardous waste.

- **Wash oil**: wash oil is consisting of 6.5-10% coal tar and other organic compositions, for example, quinoline, isoquinoline, and other valuable organic chemicals. Wash oil is used to remove coal tar from distillation fraction column. After used, it became to waste in petrochemical plant.
- **Copper slag**: copper slag is used to remove mill scale, rust, old paint, and dirt by blasting steel or concrete surface. Copper slag generated from maintenance program which need to disposal properly.

2.4.3 Waste management

In Thailand, the sustainable of industrial waste management has arisen among the increasing stress of environment. The most common methods used for industrial waste in petrochemical industry are sorting for sales, burn as fuel substitution, fuel blending, burning as co-material in cement kiln, incineration, and landfill.

(1) Sorting for sales

The basic method but high efficiency for waste management is sorting waste to separate the valuable material for reuse or recycling. Segregation of waste may be carried out by manpower or machines, depending on the types of waste. In petrochemical industry, for instance, aluminium scrap, iron scrap, paper scrap, plastic scrap, stainless scrap, are considered as non-hazardous waste. These waste types were separated for sale in recycling factory.

(2) Burn as fuel substitution

Wastes generated in petrochemical factories have comprised of various type of wastes. More than a half is contaminated with oil and has primarily an organic composition; therefore, burning waste for energy recovery is a promising option. The type of wastes, for instance, coke, lube oil/used oil, wash oil, yellow oil, oligomer, chemical cleaning waste, polymer and waste oil are regularly burned as fuel substitution.

(3) Fuel blending

Even though some waste types have a low heating value, the heating value can be adjusted by mixing petrochemical waste with other materials prior to burn. Fuel blending is waste mixing process to adjust the heating value, which can be used as alternative energy to operate in cement kiln, industrial furnace, or incinerator. Waste fuel must have heating value of at least 5,000 BTU per pound to be considered for fuel blending. Wastes applied with this procedure are activated carbon, molecular sieve, oily sludge, Monoethanolamin (MEA) mixed water, sand contaminated with oil & chemical, tars, contaminated garbage, and oil filter. Normally, fuel wastes are passing through fuel blending process prior to disposal by burning as fuel in cement kiln. Waste fuels are blended with coal or oil to produce extreme temperature which needs to convert limestone to calcium oxide. Calcium oxides become cement clinker which is raw material for Portland Cement production.

(4) Burn as co-material in cement kiln or rotary kiln

Burn as co-material in cement kiln or alternative fuel raw material (AFR) is one of the promising waste management that has shown positive impact to environment. In the United States, this procedure typically burn hazardous waste for energy recovery and material recovery as first priority, while waste treatment is secondary benefit (USEPA, 2009). Waste is destroyed by burning completely and brings back the materials that are beneficial to incorporate into a homogeneous cement product. The type of wastes, for instance, packaging wastes, waste oils, sludge from wastewater treatment plant, and spent solvents, are generally used for co-processing in cement plant (SCIeco, 2011). Sometime waste composition is not always accepted directly for co-processing. The preparation process is necessary to prepare or adjust waste composition from different waste sources before feed into AFR process that conform to technical and requirement of cement production (GTZ-Holcim, 2006).

The advantages of this method are reducing greenhouse gas emissions, reducing landfill waste, and reducing environmental impact on the ecosystem.

(5) Incineration

Incineration used as a first objective for waste destruction, however, recovery energy can occur (USEPA, 2009). Incineration can help to reduce the volume of waste and transform waste to ash, air pollution, dust, and heat. Heat recovery from burning waste can be used to produce electricity. By the way, most of incinerators emit toxic pollutant in form heavy metal like vanadium, manganese, chromium, nickel, arsenic, mercury, lead and cadmium which are also remaining residues of burning in form heavy ash and fly ash. Both heavy and fly ashes are disposed of by landfill. Incinerator technique has very famous in United States, Europe, and Japan. In Thailand, however, there is only one incinerator plant that can operate for destruction industrial waste (both non-hazardous and hazardous waste). The type of waste disposed of by this method must be highly hazardous wastes, for example, dimethyl disulfide, and infected municipal wastes.

(6) Landfill

In Thailand, Landfills can be divided into two types such as sanitary landfill and secure landfill. Sanitary landfill applied with municipal waste which has not hazardous characteristics. Secure landfill applied with hazardous waste which need pre-treatment by stabilized before added to landfill. Landfills have several occurred disadvantages, it can cause of pollutant contaminated in soil which creates long term problem of groundwater system and affect to human health and the environment. However, this method has popular to apply with wastes from petrochemical industry due to low cost of disposal. Bio-sludge and woodchip debris are applied with sanitary landfill. Type of wastes disposed of by secure landfill, for instance, metal contaminated chemicals (Pall ring), copper slag, contaminated container, and insulation.

2.5 Literature reviews

2.5.1 3R Approach

Yoshida et al. (2007) introduced 3R strategies for the establishment of an international sound material-cycle society (Yoshida et al., 2013). In this study, they focused on the promotion of the "3Rs" – reduce, reuse, and recycle. The strategy to promote 3R should be included comprehensive scheme which covered both upstream side (at the section of design and manufacturing) and the downstream side (at the section of waste treatment and disposal). In addition, it should be covered the effort to recycle and recover energy with appropriate cost operating for the 3Rs options. The author also suggested that 3Rs could be integrated into the concept of environmentally sound material management in cooperation with foreign countries.

Damanhuri et al. (2009) investigated the municipal solid waste flow in the Bandung metropolitan area, Indonesia (Damanhuri et al., 2009). This study was conducted by gathering the data from 739 units in Bandung city, and 174 units in Cimahi city. From the municipal solid waste flow analysis, they found that the composting and recycling by all stakeholders has less than 10% of the total organic waste generation. In case of inorganic waste, it was found that only 8% of total waste generation was recycled. They concluded that the result of this study should be used as an informational source to develop the MSW management policy; in addition, the difficulty of finding disposal sites in the future will be resulted in attracting to the 3R concept.

Sakai et al. (2011) published the international comparative study of 3R and waste management policy developments (Sakai et al., 2011). This study compared the policy of 3R and waste management in the European Union (EU), USA, Korea, Japan, China, and Vietnam. The result indicated that the direction of 3R and waste management policy could be divided into three directions such as:

(1) Promotion of 3R policy to prevent final disposal in landfill. The factor of 3R development has been varied, in which depended on the situation of each country. In Japan, the lack of disposal site area was the driving force to 3R development and advanced incinerator technology which have been operated as national level, simultaneously with the awareness of dioxin emission issue. In case of EU and Korea, composting of organic waste is more favorable component of their 3R options.

(2) Secure resources in experiencing rapid economic growth countries. This direction has attended to the developing countries, for instance, China, and Vietnam. These countries have been alert for importing recycled raw material which resulted in the poverty of taking 3R option to repress the import of hazardous materials. The management of hazardous waste should be proposed as first priority over other 3R measures.

(3) Third direction is aimed to develop an integrated policy centered on 3R to provide synergistic effects on waste management, prevention of natural resources, and constriction of greenhouse gas emission.

The author proposed that the challenge of 3R concept is the revolution in the sense of 3R as a code of conduct on waste management.

2.5.2 Petrochemical waste management

Abduli et al. (2006) studied the management of industrial solid wastes in order to minimize the negative effect on environment (Abduli et al., 2006). The different types of solid wastes generated in petrochemical complex including non-hazardous and hazardous wastes were studied and collected from the survey. They found that some types of waste can reuse/recycling, however, treatment and disposal options are still important tools for disposal waste. In addition, the result identified that source recovery and waste collected in suitable practices were the main options of solid waste management in petrochemical plant. Some strategies were introduced, for example, considered waste handling and waste disposal in different unit with close attention to low production, prepared edition and presentation of required law and standards especially hazardous waste, and determination type of waste for incinerator system. Source reduction can be success, for example, re-engineering of by product, management improvements activity, and using non-hazardous waste as a substitution for hazardous wastes. All of measures have shown both direct (e.g. waste treatment cost reduction) and indirect benefits (e.g. improved community relations, improved public health, legal liabilities and societal cost reduction).

Alshammari et al. (2008) studied solid waste management in petroleum refineries. This research aimed to development and testing of multi-objective planning model based on the goal programming approach for proper treatment and disposal (Alshammari et al., 2008). Types of solid waste used in this study were off-spec sulphur, refinery sludge, extraction clay, alkylating clay, lube oil processing clay, clay filtering, and spent catalyst. Twelve thermal treatment technologies were defined as alternative waste management, such as Liquid Injection (LI), Fluidized bed process (4 systems), molten glass process, wet oxidation process (4 systems), rotary kiln, third party treatment, and catalyst recovery by high thermal treatment; in addition, the other treatment processes were also considered, for example, chemical treatment technology (organic extraction and solvent extraction), physical treatment unit (encapsulation unit and stabilization unit), and land treatment facilities (landfill and land treatment). The results of multi-objective optimization model showed that the model can provide cost effective for waste disposal based on alternative treatment options. As a result, the model could be used to assist the decision making of solid waste management in petroleum industry.

Demirbas (2011) has reviewed waste management system concept and waste management system. Demirbas stated that waste management is composing of collection, transport, processing, recycling or disposal, and monitoring of waste material (Demirbas, 2011). The goal of waste management concept consists of five main goals such as: increasing of reduction and recycling wastes to reduce total amount of waste; recycling and re-introduction of wastes groups into production cycles as secondary raw material or renewable energy; re-introduction of biological waste by composting or the other ways into the natural cycle; minimize amount of waste before send to landfill. Waste management concept should be flexible to receive fluctuation in waste quantities and the composition of domestic waste. In addition, waste management system was purposed to make sure that the waste materials were removal from the source or location where they were generated, treated, and disposed of or recycled in a safe and suitable manner. Advanced waste management system should be included prioritized management strategies to minimize environmental problem and preserve resources. Waste management strategies were categorized into four areas with respect to their final disposition of the waste such as: minimization or prevention of waste generation; recycling of waste; thermal treatment with energy recovery; and land filling.

Lin et al. (2012) conducted the research on the emission of CO_2 from a Steel Mill and a Petro-Chemical Industry in Taiwan (Lin et al., 2012). As a tremendous source of energy consumption, the petrochemical industry consumed energy contributes up to 10% of total energy consumed in Taiwan. The objective of this study was to enhance the efficiency of energy consumption and reduce the GHG emission. After the innovative steam-network was applied, it can reduce heavy fuel oil consumption equal to 63,420 tons and also reduce CO_2 emission equal to 177,513 tons of CO_2. The authors suggested that this innovative could be applied in other locations to improve the energy efficiency and reduce greenhouse gas emission.

Moharamned et al. (2013) gathered the data on petrochemical productions and the distribution of their product at Shazand Petrochemical Company in Iran (Moharamned et al., 2013). The objective of this study aimed to calculate the Greenhouse Gas emission (GHG) of petrochemical process and monitoring carbon footprint across petrochemical supply chain. Results illustrated that total GHG emissions in supply chain of petrochemical case study was 6.11 million tons of CO_2-eq per year in which 99.84% of total GHG was generated from the manufacturing section, while the rest was generated from the distribution section. From the result, they suggested that green supply chain should be introduced to the petrochemical supply chain for reducing GHG emissions.

Hu et al. (2013) reviewed the recent development in the treatment of oily sludge from petroleum industry (Hu et al., 2013). They found that oily sludge from petrochemical industry has generated in tremendous quantity in each year. It was estimated that every 500 tons of crude oil will produce one ton of oily sludge waste. From the annual data of crude oil production, it could be concluded that more than 60 million tons of oily sludge will be produced every year, in addition, more than 1 billion tons of oily sludge has been accumulated throughout the world. From the review, it can be identified that oily sludge contains several of heavy metals such as zinc (7-80 mg/kg), lead (0.001-0.12 mg/kg), copper (32-120 mg/kg), nickel (17-25 mg/kg), and chromium (27-80 mg/kg). Various methodologies of recycling and disposal of oily sludge have been reviewed; however, the author suggested that there is no single specific process could be selected due to each methodology has related with different advantages and limitations.

Pombo et al. 2013 studied on the analysis of water management in Brazilian petroleum refineries by using rationalization techniques (Pombo et al., 2013). With the average water consumption index (WCI) of the case study refineries (0.9 m^3 of water/m^3 of oil processed), it was estimated that water consumption was 203,438 m^3 of water per day. This study applied the conservation, the reused of water techniques, and also pinches techniques to identify the suitable technique for reducing of water consumption. As a result, it was found that water pinch technique could assist for reducing water consumption by almost 40-50%. Among techniques of treatment, they suggested that nanofiltration and ion exchange should be applied as the final step of reverse osmosis, and advanced oxidative processes, to increase the efficiency of treating sourwater.

CHAPTER III

METHODOLOGY

3.1 Literature review and data gathering

Investigation of existing environmental performance of petrochemical process was a first step in this study. Secondary data, for instance, Thailand’s petrochemical production overview, policy and legislation involved in waste management in Thailand, were gathered from relevant studies or relevant institutions.

3.2 3R approaches methodology

The methodology used in this study was divided into two subsections. The details of each subsection are:

3.2.1 Field surveying

The waste storage facility and waste treatment system of the petrochemical plant were surveyed. The types of data obtained at this stage include the sources of waste, types of waste, amounts of wastes, and existing waste management practices. After the survey was finished, the meeting between the research team and the person responsible for waste management at the petrochemical plant was conducted. Then, research team analysed the data obtained under the following topics:

- **Waste classification**

  Data on waste sources, waste types, and quantity of waste were identified.
- **Existing waste management options**

  Data on existing waste management options at the petrochemical plant were gathered and analyzed to determine appropriate waste management options.

3.2.2 Proposing 3R options

This part focuses on the minimization of waste, and reuse and recycling of wastes according to 3R concept. All data collected in the first step was used as guidelines and inspiration to select appropriate measures for minimizing the environmental impacts of the petrochemical plant. After the proposed 3R was completed, the guideline for improving waste management was established and to be followed in the handling of industrial waste. The schematic of the study is shown in Figure 3.1.

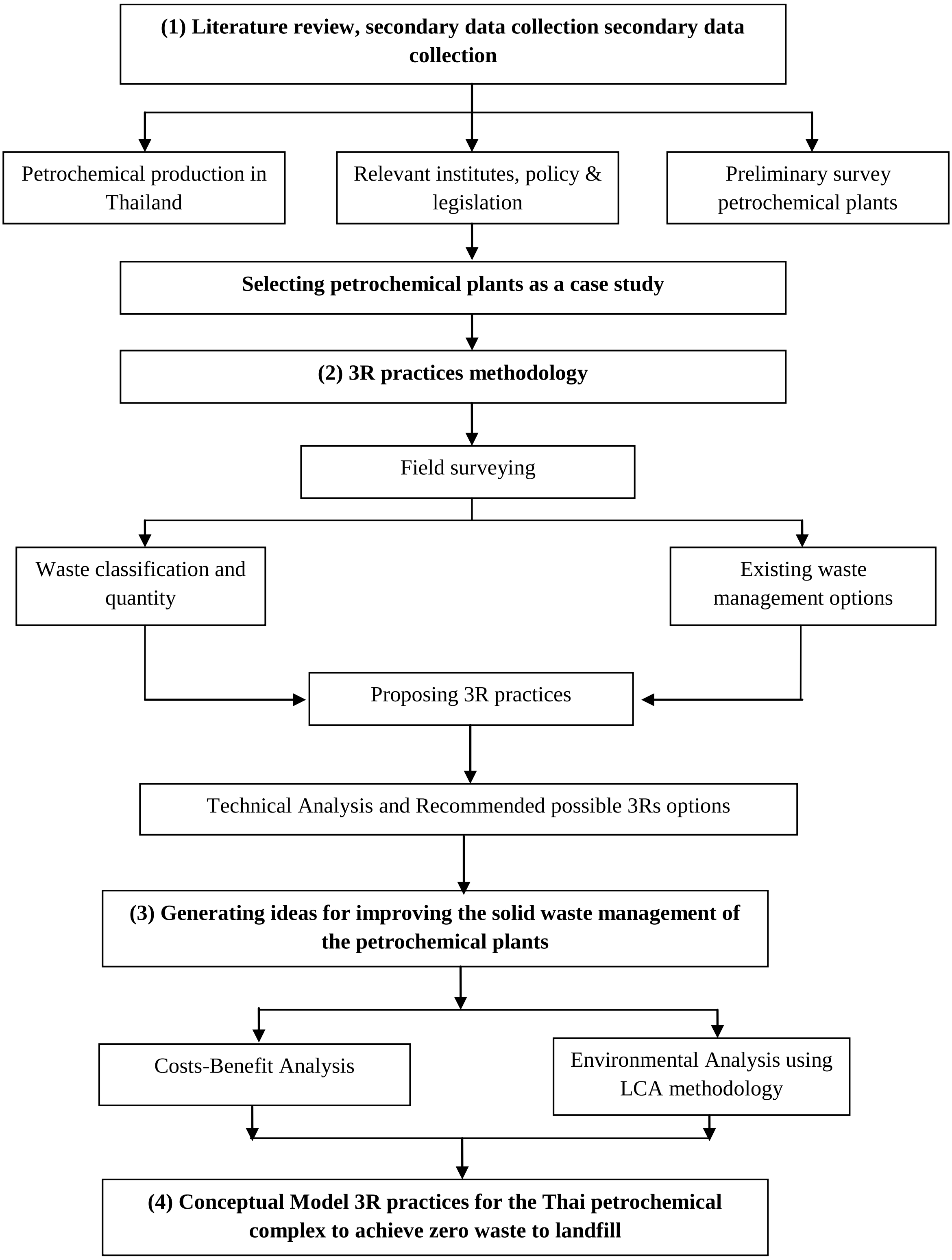


Figure 3.1 Flow diagram of the study

3.3 Environmental impact analysis

This step, life cycle assessment (LCA) was used as a tool to determine the different resulted of environmental impact in each alternative waste management. The goal of this step was to evaluate the environmental impact from the existing industrial solid waste management systems compared with proposed 3R practices based on life cycle perspective.

Goal and scope

The objective of this step was to identify the environmental impact of the waste management options from petrochemical plant. Either direct process related to waste management systems or other relevant processes interacting with the system were also included. The disposal of 1 ton of industrial waste was used as a functional unit. The boundary was started from waste transportation at petrochemical factory until industrial waste was disposed of at waste processor plant.

Inventory Analysis

The emission to the environment were evaluated from each waste management option. Waste incineration was based on the data of chemical characteristic of wastes and the efficiency of the incinerator. The estimating of the emissions from coal and waste were obtained using the latest update of the ECO-invent database version 2.1.

Impact Assessment

The environmental impact from each scenario was calculated at mid-point and damage level using IMPACT 2002+ method due to it is the most recent updated indicator approach available in LCA analysis, especially for the comparative assessment of human toxicity and ecotoxicity (Jolliet et al., 2003). This model also combines the data of other models, such as CML (Guinee et al., 2002) and Eco-indicator 99 (Goedkoop and Spriensma, 2000), to investigate 17 mid-point categories including human toxicity (including carcinogens and non-carcinogens), respiratory effects (due to inorganics), ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification, land occupation, water turbined, global warming, non-renewable energy consumption, mineral extraction, water withdrawal, and water consumption (Humbert et al., 2012). These mid-point will be linked to four damage categories (human health, ecosystem quality, climate change, and resources). Selected pollutants in this study were based on laboratory results in which they affect in nine impacts such as: the impact of Global Warming Potential (GWP), Acidification Potential (AP), Respiratory Inorganic (RI), Terrestrial Acidification and Nitrification (TAN), Aquatic Eutrophication Potential (AEP), Aquatic Ecotoxicity (AE), Terrestrial Ecotoxicity (TE), Non-Carcinogenic Effects, and Carcinogenic Effects.

Interpretation

The results of impact assessment section were interpreted. The suggestion and recommendation of solid waste management from petrochemical plant were generated in this section.

3.4 Conceptual Model 3R practices for the Thai petrochemical complex to achieve zero waste to landfill

The concept of 3Rs with hierarchy of waste management is based on reduce the total amount of waste until zero waste to landfill. Combinations of the previous step are used to develop a conceptual model 3R practices for the Thai petrochemical complex to achieve zero landfill waste. Technical options are selected based on the consideration of environmental performance, available technology, and economic feasibility.

3.5 Case study description

Upstream petrochemical case study plants

In this study, three olefin plants were selected as case studies to create the strategy of improving waste management system. These case study plants were applied in Chapter 4. Every case study plant was located in the Map Ta Phut Industrial Estate (MTPIE), Rayong province, Eastern of Thailand. Olefin plants employ a steam cracking process with a total capacity in the range of 590,000 to 1,000,000 tons per year. Ethane and naphtha are the main components of the feedstock to produce ethylene and propylene. The process flow diagram and industrial waste generation can be illustrated in Figure 3.2.

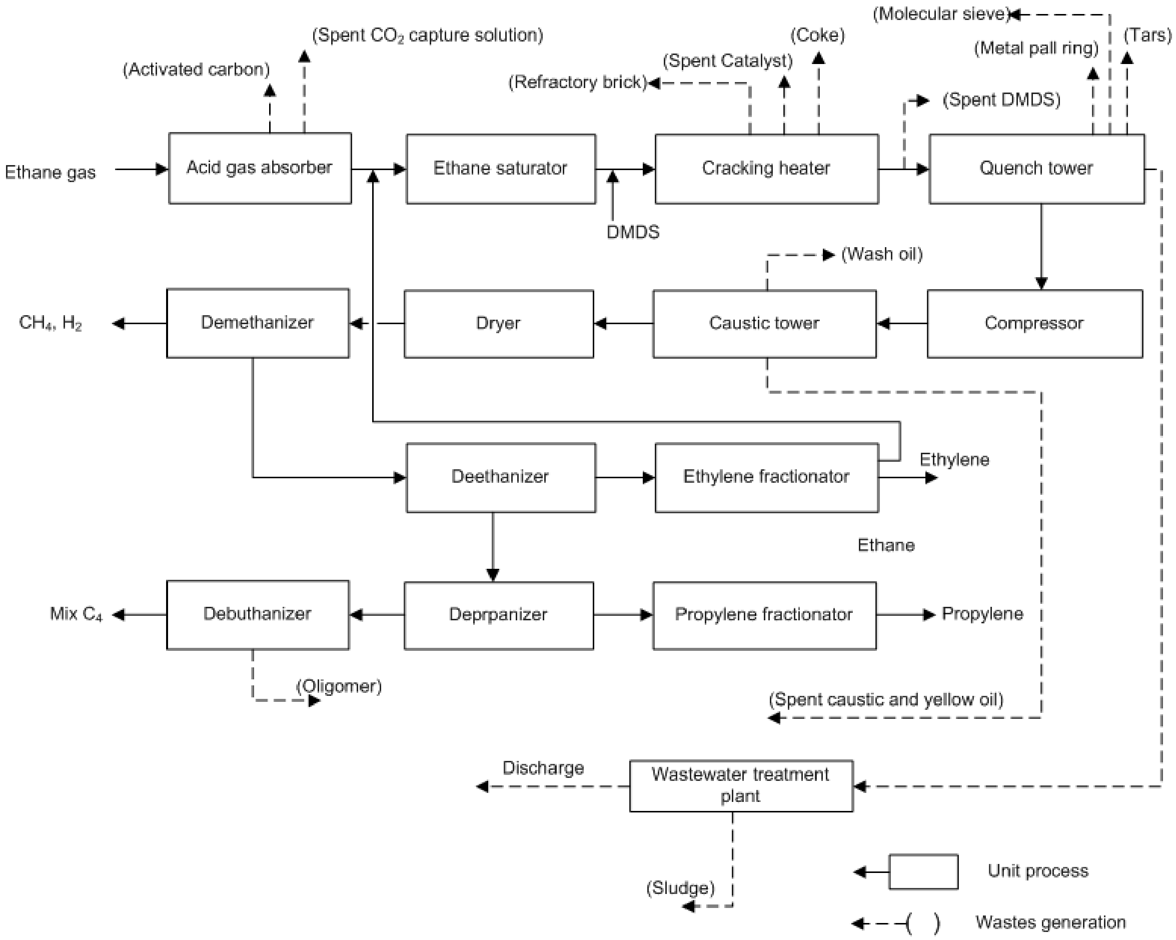


Figure 3.2 Schematic diagram of the olefin production process of case study plants.

Downstream petrochemical case study plants

(1) HDPE case study plants

Two HDPE factories were selected as the case study plant. One plant was applied in Chapter 5, while another one was applied in Chapter 7. The factory produces high density polyethylene as its main product and has a production capacity in the range of 300,000 - 500,000 tons per year. The factory is located in the Map Ta Phut Industrial Estate (MTPIE), Rayong province, in Eastern Thailand.

The process for producing high density polyethylene is illustrated in Figure 3.3. First, catalyst solution is mixed with a solvent (hexane) in the catalyst solution preparation unit. The pressure of this unit is between 1 - 20 atm. Then, this solution is passed to the HDPE reactor. At the HDPE reactor unit, ethylene is introduced into the reactor vessel as a gas (at a pressure condition between 1-20 atm) to react with the active site of the catalyst to produce polyethylene. Hexane is used as the solvent to dispel heat in the reactor. At the exit of the HDPE reactor unit, polyethylene is generated, which has melting point approximately 130 degrees Celsius. Hence, the polyethylene is formed in a solid state, which is called slurry polymerization or suspension polymerization. At the fractionators unit, hexane and un-reacted ethylene are separated from the polyethylene for reuse in the process again. Then polyethylene is recovered using the extruder and drying units. Finally, polyethylene is sent to pellet classifier unit and is ready for use at bulk product weight hopper unit.

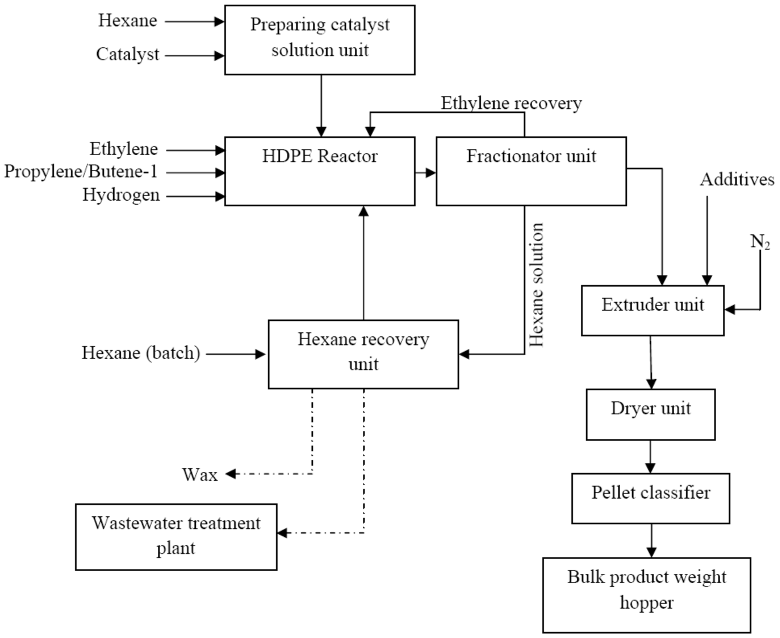


Figure 3.3 Simplified flow diagram of the HDPE production process of case study plants

(2) LDPE/LLDPE case study plant

LDPE/LLDPE factory was selected as the case study plant; however, the factory was divided into two units such as LDPE unit for producing low density polyethylene and LLDPE unit for producing linear low density polyethylene. The capacity of producing LDPE is 300,000 tons/year and LLDPE is 400,000 tons per year. This factory was applied in Chapter 7.

CHAPTER IV

DEVELOPMENT OF SUSTAINABLE WASTE MANAGEMENT TOWARD ZERO WASTE LANDFILL WASTE FOR THE PETROCHEMICAL INDUSTRY IN THAILAND USING A COMPREHENSIVE 3R METHODOLOGY: A CASE STUDY[1]

This chapter aimed to study how the 3R options could improve industrial-waste management in the Thai petrochemical industry with the ultimate goal of producing zero landfill waste. The 3R options were proposed and implemented at the upstream petrochemical case study plants. After the 3R options were applied to these plants, the benefits in terms of reduced cost, natural resource depletion, and greenhouse gas emissions were evaluated.

4.1 Background of case study plants

In this study, three olefin plants were selected as case studies for improving waste management systems. All three plants are located in the Map Ta Phut Industrial Estate (MTPIE) of Rayong Province in eastern Thailand. The plants employ a steam cracking process with a total capacity of 2,888,000 tons per year (as shown in Table 4.1). This capacity is approximately 74.68% of the total olefin production in Thailand. Ethane and naphtha are the main components of the feedstock that is used to produce ethylene and propylene. These products from the plants are sold as feedstock to High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE), Linear Low Density Polyethylene (LLDPE), and Ethylene Oxide/Ethylene Glycol (EO/EG) factories.

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[1] This chapter has been published in Waste Management & Research 2014; first published on May 13, 2014 as doi:10.1177/0734242X14533604

Table 4.1 Details of petrochemical case study plants

Petrochemical plant	Production capacity (ton/year)		
	Ethylene	**Propylene**	**Total**
Olefin I	461,000	127,000	588,000
Olefin II	915,000	360,000	1,275,000
Olefin III	1,000,000	25,000	1,025,000
	2,376,000	**512,000**	**2,888,000**

4.2 Waste sources and waste generation

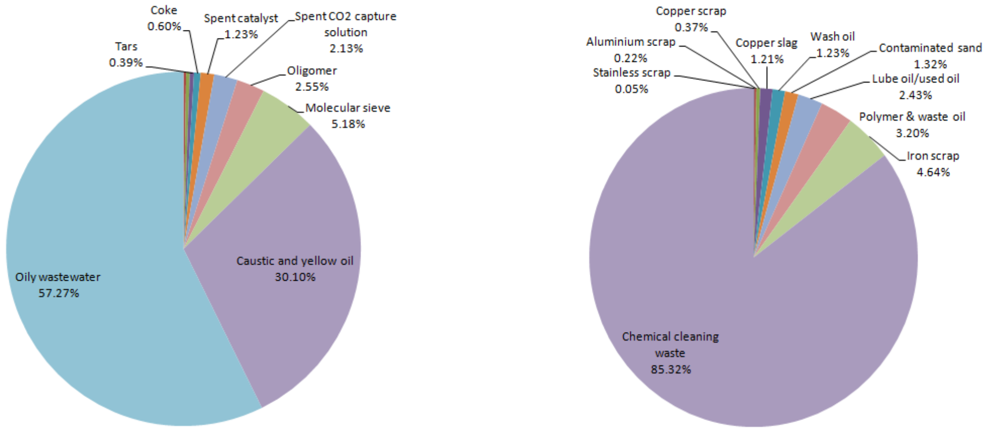
The list of industrial waste types generated by the plants is presented in Table 4.2. Forty-one different types of industrial waste were generated from the different activities of the factory, such as the production process, the maintenance program, packaging and equipment, and the waste treatment system. Some wastes (e.g., bio-sludge, metal scrap, paper scrap, wood debris, plastic scrap, aluminium scrap, and stainless scrap) were determined to be non-hazardous, and the remaining types were classified as hazardous wastes. Approximately 91% of the total waste generated was classified as hazardous waste.

Table 4.2 List of industrial wastes identified in the olefin factory.

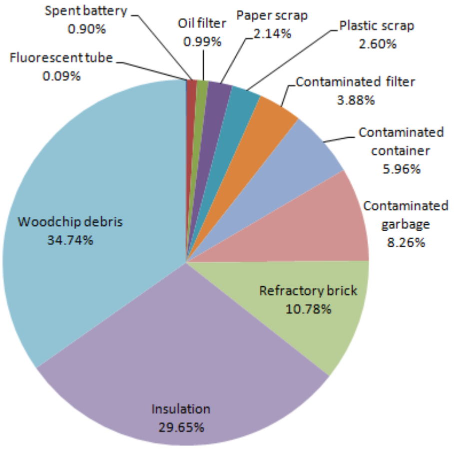
No.	Waste code	Identified waste item	Waste Types	Waste categories
1	070101	Activated carbon	Hazardous	Production process
2	150203	Air filter	Hazardous	Packaging and equipment
3	160802	Alumina ball	Hazardous	Production process
4	190812	Bio-sludge	Non-hazardous	Waste treatment system
5	070101	Caustic and yellow oil	Hazardous	Production process
6	070101	Chemical cleaning waste	Hazardous	Maintenance program
7	100113	Coke	Hazardous	Production process
8	150110	Contaminated container	Hazardous	Packaging and equipment
9	120116	Copper slag	Hazardous	Maintenance program
10	160507	Dimethyl disulfide	Hazardous	Production process
11	160601	Dry cell battery	Hazardous	Packaging and equipment

No.	Waste code	Identified waste item	Waste Types	Waste categories
12	170603	Insulation	Hazardous	Packaging and equipment
13	130206	Lube oil	Hazardous	Maintenance program
14	170409	Metal contaminated chemical substance	Hazardous	Packaging and equipment
15	070110	Molecular sieve	Hazardous	Production process
16	160709	Monoethanolamine (MEA) mixed with water	Hazardous	Maintenance program
17	150202	Contaminated garbage	Hazardous	Packaging and equipment
18	150202	Oil filter	Hazardous	Packaging and equipment
19	050103	Oily sludge	Hazardous	Waste treatment system
20	070101	Oily wastewater	Hazardous	Waste treatment system
21	070214	Oligomer	Hazardous	Production process
22	190810	Polymer and waste oil	Hazardous	Production process
23	161105	Refractory brick	Hazardous	Packaging and equipment
24	190813	Sludge	Hazardous	Waste treatment system
25	160807	Spent catalyst	Hazardous	Production process
26	070101	Spent caustic	Hazardous	Production process
27	051008	Tar (pH 5)	Hazardous	Production process
28	130206	Used oil	Hazardous	Maintenance program
29	070208	Waste oil	Hazardous	Maintenance program
30	161002	Wastewater	Hazardous	Waste treatment system
31	070208	Yellow oil	Hazardous	Production process
32	170405	Metal scrap	Non-hazardous	Packaging and equipment
33	150103	Wood debris	Non-hazardous	Packaging and equipment
34	150101	Paper scrap	Non-hazardous	Packaging and equipment
35	170203	Plastic scrap	Non-hazardous	Packaging and equipment
36	170405	Stainless scrap	Non-hazardous	Packaging and equipment
37	170402	Aluminium scrap	Non-hazardous	Packaging and equipment
38	160601	Spent battery	Hazardous	Packaging and equipment
39	150110	Drum metal (200 l)	Hazardous	Packaging and equipment
40	150202	Sand contaminated with oil and chemical substances	Hazardous	Maintenance program
41	160215	Fluorescent tube	Hazardous	Packaging and equipment

Production processes and maintenance program activities are the main sources of waste generation; these activities account for up to 45.18% and 36.71% of the total waste, respectively, followed by the waste treatment system (9.73%) and packaging (8.37%). The data in Figure 4.1 indicate the types of waste generated by each waste source activity. As shown in Figure 1a, most of the waste produced during the production processes consists of oily wastewater and caustic and yellow oil. These wastes can be used as fuel for heating because they contain oil and chemical substances.



(a) Production process waste (b) Maintenance waste



(c) Packaging and equipment waste

Figure 4.1 Waste types from each factory activity in the olefin plants under consideration

Figure 4.1b presents ten types of maintenance wastes. Wastes in this category are generated when the petrochemical plant must be cleaned. Special chemical solutions are used to remove pollutants (e.g., heavy oils and polymer deposits) from the machines; after the pollutants are removed, the spent special chemical solutions become waste (called chemical cleaning wastes, used oil, or wash oil). These waste types can be burned for energy recovery or used in fuel blending. In addition, metal scraps are generated during the blast cleaning of steel or concrete surfaces.

Figure 4.1c presents the packaging and equipment wastes that are generated when equipment breaks down. Accidental leaks are the main cause of maintenance program waste generation. Most of these wastes are mainly composed of inorganic substances; thus, they are unavailable for energy recovery. Disposal of these wastes in landfills is a common method due to its low cost and simplicity.

From a waste management perspective, various types of wastes are more difficult to dispose of than a single waste type. Therefore, we suggest that petrochemical wastes be separated at the source before selecting the most suitable waste management option for each waste type. In addition, estimating the amount of waste generated poses another waste management challenge in petrochemical factories. The quantities of maintenance wastes and packaging and equipment wastes are difficult to estimate annually because they are not generated in proportion to the production process and the quantity of raw materials used. We sent a questionnaire to the waste manager in each factory to estimate the quantity of landfill waste generated in 2011. The results indicated that all of the waste managers underestimated the quantity of landfill waste produced at their factories.

To increase the accuracy of waste generation prediction, we suggest that all waste generators, i.e., maintenance and production departments, cooperate in estimating the waste that will be generated in a given year. Therefore, in large organisations, all departments that generate waste, and not only the environmental department, should participate in waste management operations. When source reduction is the first priority of waste management, each waste generator in the organisation should be aware of waste generation in the factory, and the environmental department should be responsible for selecting the most environmentally friendly waste disposal method.

From the data collected in 2010, the baseline level of industrial waste recycling was relatively high (see Figure 4.2). Approximately 88% of the total waste generated was properly managed. Three main waste management options were identified: fuel substitution (44%), fuel blending (36%), and landfill (7%). Although the plants have a high potential for recycling options, the landfill option is still part of their waste management strategy. For these plants, landfill waste consists of both organic and inorganic material. Inorganic wastes include insulation, copper slag, contaminated containers, contaminated metal scrap, molecular sieves, and air filters. Organic wastes include bio-sludge, sludge, wood debris, and plastic scraps.

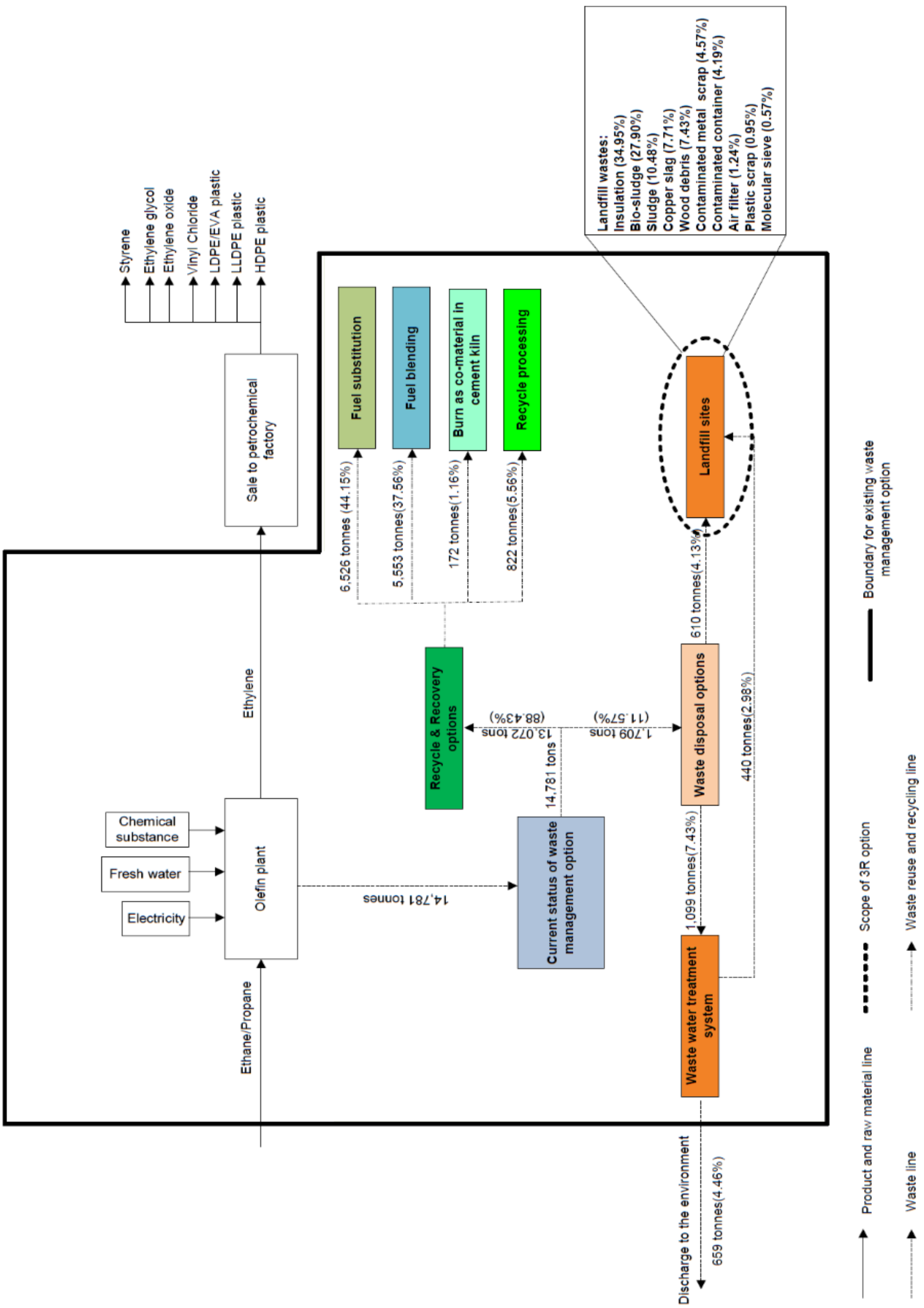


Figure 4.2 Quantified existing waste material flows of industrial wastes in the plants under consideration (waste data from 2011).

To improve the factories' waste management systems, we focused on the type of waste that was disposed of in landfills. In Thailand, landfills can be divided into two types: sanitary landfills and secure landfills. Sanitary landfills are reserved for non-hazardous waste, and secure landfills are reserved for hazardous waste.

4.3 Proposed 3R options

Options for improving the industrial waste management system are presented in Figure 4.3.

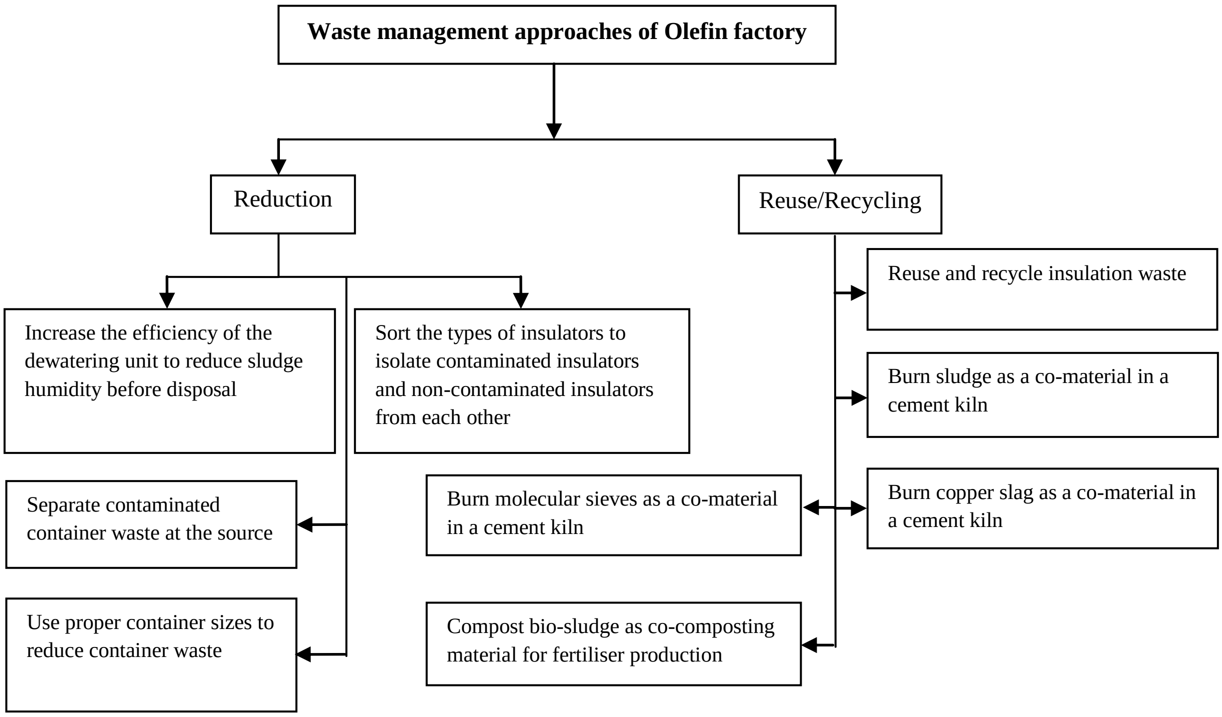


Figure 4.3 Proposed 3R options for improving waste management at the olefin factories.

4.3.1 Bio-sludge and sludge from the activated sludge wastewater treatment system

Our surveys indicated that sludge from activated sludge wastewater treatment systems can be divided into 2 types: bio-sludge and sludge. Bio-sludge refers to sludge from an activated sludge wastewater treatment system and is classified as non-hazardous waste. Sludge refers to sludge from an activated sludge wastewater treatment system and is classified as hazardous waste. Options for reducing, reusing and recycling bio-sludge and sludge are described in the following passage.

1) On-site reduction

Hydrophilic bio-sludge is difficult to dewater. Sludge volumes can be reduced by 1) improving the bio-sludge conditioning process or 2) drying the bio-sludge under sunlight prior to disposal (Wittmaier et al., 2009). The volume of bio-sludge can be reduced at the source by using various chemical conditioners to increase the effectiveness of the dewatering operations (Djedidi et al., 2009). This process can reduce the moisture content of the bio-sludge, yielding a more compact form before the sludge is disposed of at a landfill site.

2) Off-site recycling/recovery

- Recycle bio-sludge as co-composting material for fertilizer production

Bio-sludge can be used as a raw material for producing fertiliser or soil conditioners. The methodology for composting bio-sludge as a co-material to produce fertiliser was determined using data from the site visit at Micro Biotec Company Ltd. in Rayong Province, Thailand. Before implementing this option, it is necessary to determine the characteristics of the bio-sludge according to the requirements of the Department of Agriculture, Thailand (MAC, 2005). The characteristics of the bio-sludge at the olefin plants are provided in Table 4.3.

Table 4.3 Sludge characteristics at the olefin plant.

No.	Characteristics	Olefin I (Bio-sludge)	Olefin II (Sludge)	Requirement
1	Sieve size (12.5 × 12.5 mm)	90.75%	87.67%	Not more than 12.5 × 12.5 mm
2	Moisture content at 75°C, 20 h (%)	15.45%	22.8%	Not more than 35% by weight
3	Gravel (%)	Not Detected	Not Detected	Larger than 5 mm and not more than 5% by weight

4	Plastic, glass, other metal	Not Detected	Not Detected	Not detected (ND)
No.	**Characteristics**	**Olefin I (Bio-sludge)**	**Olefin II (Sludge)**	**Requirement**
5	Organic matter	73.48%	64.71%	Not less than 30% by weight
6	Organic carbon	42.62%	37.53%	
7	pH	8.2	7.7	5.5-8.5
8	C/N ratio	8/1	6/1	Not more than 20:1
9	Electrical conductivity (EC)	3.31	1.76	Not more than 6 dS/m
10	Germination index (GI; %)	62.11%	5.44%	More than 80%
11	Total nitrogen (%) Total phosphate (%) Total potash (%)	5.3% 1.8% 0.3%	6.4% 3.2% 0.4%	- Total N not less than 1.0% by weight - Total P_2O_5 not less than 5% by weight - Total K_2O not less than 0.5% by weight
12	Arsenic Cadmium Chromium Copper Lead Mercury	6.5 6.1 190 62 54.6 13.2	3.4 0.84 212.4 103.8 904.3 15	Not more than 50 mg/kg Not more than 5 mg/kg Not more than 300 mg/kg Not more than 500 mg/kg Not more than 500 mg/kg Not more than 2 mg/kg

The properties of the bio-sludge are similar to the standard requirements for organic matter, the germination index, and total nitrogen. Whereas the bio-sludge has a germination index of 62%, the olefin II sludge has a germination index of 5%. Therefore, the bio-sludge of Olefin 1 can be composted by mixing it with sawdust and microbial inoculums. The fertiliser production yield is 0.2 ton of fertiliser per ton of sludge.

- Burn sludge as a co-material in a cement kiln

Sludge, classified as a hazardous waste, cannot be composted to produce fertiliser. Both bio-sludge and sludge can be burned as a co-material in cement kilns. Sludge can be burned to recover energy, and the sludge residues can be used as replacement materials in cement clinkers (Monte et al., 2009). From the analysis, the heating value of sludge is 18,513 MJ ton^{-1}. Given the quantity of sludge that was generated in 2011 (185 tons), it is estimated that the maximum amount of energy that can be recovered by burning the sludge is approximately 342,491 MJ year^{-1}.

4.3.2 Insulation waste

Moisture, oil, and other chemical substances often contaminate insulation when they are not stored properly. Our survey indicated that insulation wastes were not stored separately by type and that contaminated insulation waste was not stored separately from non-contaminated insulation waste. Under these conditions, the entire volume of insulation wastes had to be disposed of in a secure landfill as hazardous waste. To improve the waste management system with respect to insulation wastes, 3R options were proposed, beginning with waste reduction at the source. Details are provided below.

1) On-site reduction

Adequate planning and management before insulation demolition can reduce waste generation. The separation of insulation wastes by insulation type and the reuse of uncontaminated insulation on site are best practices for waste management. In this study, a sorting unit was installed to separate types of insulation waste and to store reusable insulation carefully to prevent contamination. After the sorting unit was installed, we found that four types of insulation were employed in the factory: rock wool (51.73%), refractory brick (39.31%), foam glass (7.23%), and polyurethane foam (1.73%).

2) Off-site recycling/recovery

- Recycling/recovery in a cement kiln

Some types of insulation waste, e.g., polyurethane and refractory brick, can be diverted from landfills and burned as an alternative fuel and co-material in cement kilns. Refractory brick can be incinerated to replace raw materials, and polyurethane can be incinerated as a substitute for conventional energy.

4.3.3 Contaminated containers

According to the survey data, waste containers were not classified and separated during the survey period. All types of contaminated containers were classified as hazardous waste and were sent to landfills. The following 3R options are proposed.

1) On-site reduction/reuse

- Installing a sorting unit to reduce contaminated containers at the source.
- Using larger containers to reduce the amount of packaging waste.
- Changing from using liquid chemicals to using powdered chemicals to reduce the amount of packaging for transportation.
- Modifying the packaging structure so that packaging can be re-used.
- Creating a large waste container for waste collection to reduce the use of small containers.

2) Off-site recycling/recovery

After a separation unit is installed, the options for each container type are as follows:

- Used metal cans can be sent to a smelter factory; however, a compressing machine is necessary to reduce the waste volume before recycling.
- Plastic containers can be burned in an incinerator for energy recovery; however, they should be shredded before burning to increase the contact surface.

4.3.4 Copper slag and molecular sieves

1) Off-site recycling/recovery

Recycling/recovery in cement kiln

Molecular sieves are used to remove water in the feedstock during olefin production. The sieves are made from a synthesized zeolite compound, and they become deactivated after a certain period of time (Mokhtarani, 2006). Molecular sieves and copper slag are both inorganic materials; they mainly consist of Al_2O_3, Fe_2O_3, and SiO_2. A typical processing clinker uses four basic oxides for production: calcium oxide, silicon oxide, alumina oxide, and iron oxide (ECA, 2013). Therefore, molecular sieves and copper slag waste can be burned as co-materials in a cement kiln to produce cement clinker.

4.4 Implementation of the selected 3R options

As shown in Figure 4.4, the amount of landfill waste that was generated was similar for the first two years (2010-2011). However, a large amount of landfill waste was observed during the final year of monitoring because the olefin plants had performed maintenance activities in 2012 that resulted in the generation of additional waste. The 3R options were introduced to the factories in January 2011, and the project was monitored for 24 months. After the 3R options were proposed, three main options were selected for application: the burning of inorganic wastes as co-materials in cement kilns, the burning of sludge as an alternative fuel in cement kilns, and the composting of bio-sludge to produce fertiliser. In 2012, the implementation of these 3R options decreased the amount of landfill waste by approximately 79.01%.

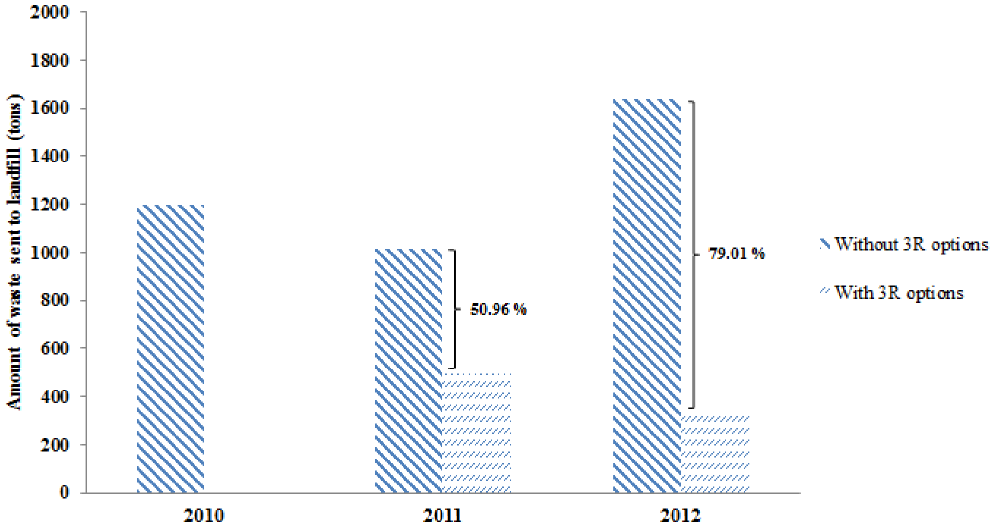


Figure 4.4 Annual waste disposed of at a landfill by the olefin plants.

4.5 Reduction of the environmental impact and disposal costs

4.5.1 Evaluation of the environmental benefits of the selected 3R options

The changes in the environmental impact are shown in Table 4.4. Each option reduces impacts to natural resources and reduces greenhouse gas emissions. Before the 3R project was implemented, the landfill waste listed in Table 4.4 (approximately 1,200 tons) resulted in a loss of usable land and potential harm to the environment. However, after the 3R options were proposed and implemented, some petrochemical wastes were used either as raw materials or as alternative energy sources for other factories, thus reducing the amount of depleted natural resources and greenhouse gas emissions. However, it should be noted that the environmental impact in this section will be determined only avoided emission from substitution conventional fuel. The full life cycle assessment will be shown in Chapter VI.

4.5.2 Cost comparison of the waste disposal methods

As shown in Table 4.5, the cost of waste disposal was estimated during a site visit to the olefin plant (personal communication, June 1, 2011). The waste disposal cost depends on the characteristics of the waste products. In case of landfill waste, hazardous waste tends to have a higher disposal cost than non-hazardous waste. The total cost of waste disposal was reduced by 453,308 baht/year when industrial waste was diverted from landfills and disposed of using a more environmentally friendly method.

Table 4.4 The environmental impacts of the selected 3R options (data collected in 2012).

The environmental impacts of the selected 3R options (data collected in 2012).

Type of waste	Selected option	Reduction in landfill waste (tons)	Reduction in the depletion of natural resources (tons)	Emission factor of greenhouse gas emissions (ton CO_2 eq/ton natural resource)	Reduction in greenhouse gas emissions (tons CO_2 eq)
Sludge	Burn sludge as an alternative energy in a cement kiln	386.51	30 tons of bituminous coal[a]	2.94	88.06
Molecular sieves, copper slag, refractory brick	Burn inorganic wastes as raw materials in a cement kiln	698.29	333.65 tons of clay[b]	0.0028	0.92
Bio-sludge	Co-compost bio-sludge to produce fertiliser	122.13	24.43 tons of fertiliser	2.6	63.51

[a] Considering average solid content at 10%, and using 18,513 MJ per ton of sludge for calculation.

[b] The amount of clay substituted was based on Al_2O_3 content (132.46 tons) in inorganic wastes. The calculation used 0.3970 ton of Al_2O_3 per ton of clay (CMS, 2013).

[c] The fertiliser production yield is 0.2 ton of fertiliser per ton of sludge.

Table 4.5 The cost saving of the selected 3R options.

Table 4.5 The cost saving of the selected 3R options.

Type of waste	Selected option	Reduction in landfill waste (tons)	Cost of disposal		
			Landfill (baht/ tons)	3R options (baht/tons)	Cost savings (baht)
Sludge	Burn sludge as an alternative energy in a cement kiln	386.51	5,581	4,584	385,350
Molecular sieves, copper slag, refractory brick	Burn inorganic wastes as raw materials in a cement kiln	698.29	1,900	1,400	61,065
Bio-sludge	Co-compost bio-sludge to produce fertiliser	122.13	3,700	3,690	6,893

4.6 Discussion of the proposed 3R options

Wastes from petrochemical factories can be used as raw materials in the agriculture and cement industries. Based on the analysis of the industrial waste flow, a model of almost-zero landfill waste for the petrochemical industry is presented in Figure 4.5. Figure 4.5 presents a schematic diagram of optimum waste management for the olefin production industry that can be used to achieve environmental balance in an industrially complex society. According to the data collected in 2012, 1,639 tons of landfill waste were generated, consisting of 463.19 tons of molecular sieves, 399.37 tons of bio-sludge, 386.51 tons of sludge, 234.40 tons of insulation waste, 116.53 tons of copper slag, and 26.05 tons of contaminated containers. To achieve 79% landfill waste reduction, waste reduction at the source was applied to the sludge, whose moisture content was reduced with solar drying. After a sorting unit was installed in the factories, the reuse option was successfully applied to insulation waste and contaminated containers. Approximately 3 tons of insulation waste and 7.22 tons of contaminated containers were reused in the factory. Recycling also plays an important role in reducing landfill waste. Molecular sieves, copper slag, and refractory brick were used as raw materials in the clinker process. Based on the calculations, 222.27, 132.46, and 64.38 tons of SiO_2, Al_2O_3, and Fe_2O_3, respectively, were contained in these wastes. These minerals can be used to replace a portion of the clay needed in the clinker process.

In addition, the sludge was used as an alternative energy source to generate 715,527 MJ of energy. This energy can be used as a substitute for approximately 30 tons of bituminous coal. When using bio-sludge as a co-composting material for fertiliser production, the nutrient contents in the bio-sludge (i.e., 21.17, 7.19, and 1.20 tons of N, P, and K, respectively) are resilient to the environment. Unfortunately, only 122.13 tons of bio-sludge was recycled as fertiliser because of the limited capacity of fertiliser production in Thailand.

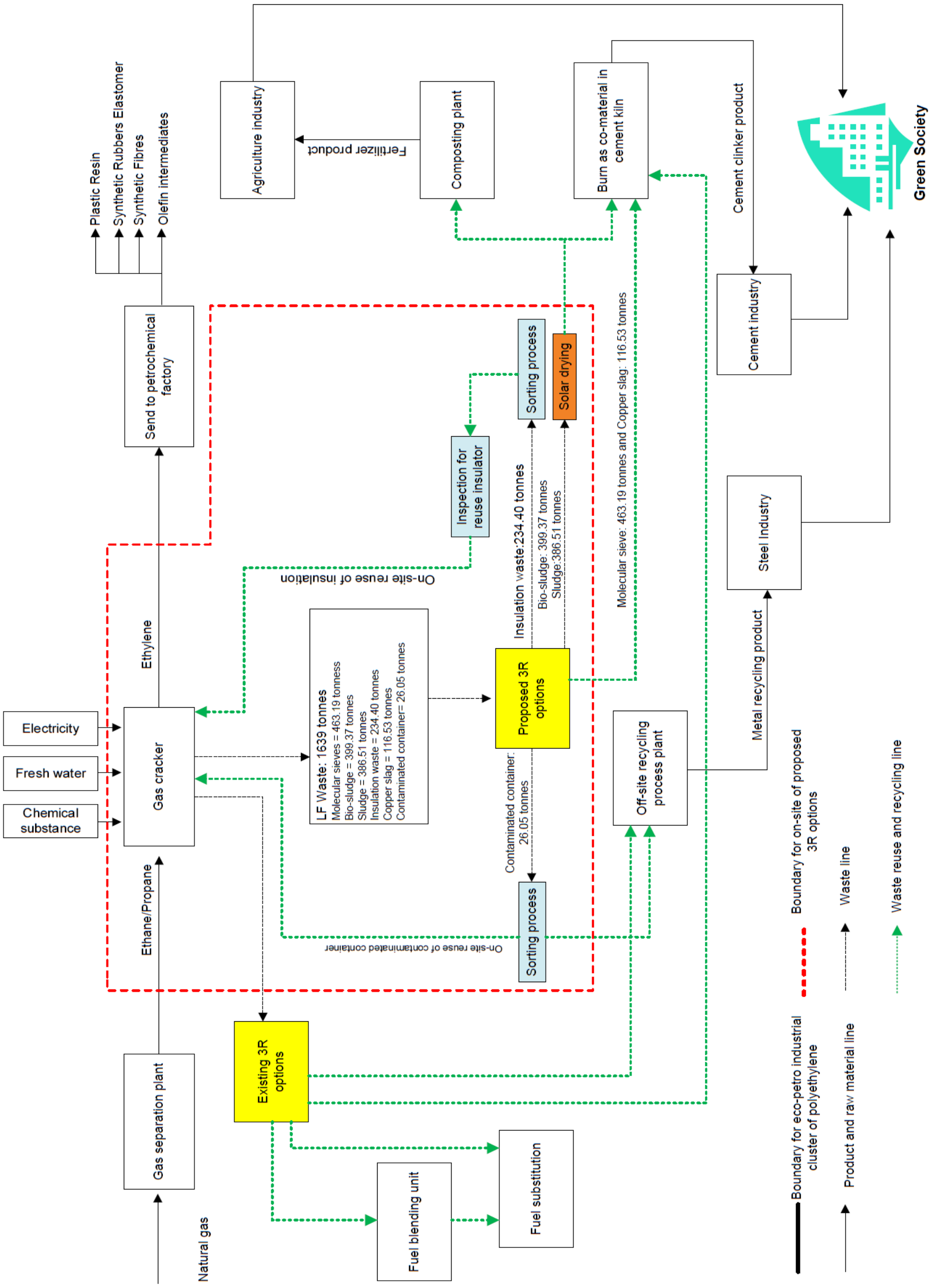


Figure 4.5 Schematic diagram for optimum waste management for the olefin production industry.

4.7 Conclusions

Based on the data obtained, most of the wastes generated by the selected plants are classified as hazardous wastes. The Thai petrochemical plants considered here exhibit a high level of industrial waste recycling. However, they also dispose of various waste types, such as bio-sludge, sludge, insulation, copper slag, molecular sieves, and contaminated containers, in landfills. The comprehensive 3R methodology was applied to divert landfill waste to the recycling stream. Various options were introduced to improve the waste management system. Three main options were selected, and the implementation of these options reduced the amount of landfill waste by approximately 79.01%. However, some types of waste, such as rock wool, are still being disposed of at landfills. Although a sorting process improved the insulation waste management system, the insulation wastes that cannot be reused are still disposed of at landfills because Thailand does not possess the technology to recycle those types of waste.

The 3R strategy can be used to improve the sustainability of industrial solid waste management systems by the following methods:

- Reducing waste at the source by using a sorting process,
- Increasing the rate of reuse as a result of waste sorting, and
- Increasing the rate of recycling, which this results in reduced natural resource depletion.

Landfill wastes were reduced by employing the 3R options at the plant; furthermore, disposal costs and the use of raw natural resources were reduced. Sustainable procurement and extended producer responsibility should be introduced to factories to increase the effectiveness of the 3R methodology and reduce waste generation at the source.

CHAPTER V

OPTION FOR SUSTAINABLE INDUSTRIAL WASTE MANAGEMENT TOWARD ZERO WASTE LANDFILL IN A HIGH DENSITY POLYETHYLENE (HDPE) FACTORY IN THAILAND [2]

This chapter mainly focuses on the reduction, reuse and recycling of solid industrial wastes. LCA methodology is used as a tool to determine the environmental impact after 3R options were adopted which were shown in section 5.6. Furthermore, the cost comparison of waste disposal is also investigated. The HDPE factory is used as a case study to illustrate how 3R strategies can be employed to address waste management issues.

5.1 Background of case study plants

High Density Polyethylene (HDPE) factory was selected as the case study plant. The factory produces high density polyethylene as its main product and has a production capacity of 500,000 tons per year. The factory is located in the Map Ta Phut Industrial Estate (MTPIE), Rayong province, in Eastern Thailand.

The process for producing high density polyethylene is illustrated in Figure 5.1. First, catalyst solution is mixed with a solvent (hexane) in the catalyst solution preparation unit. The pressure of this unit is between 1 - 20 atm. Then, this solution is passed to the HDPE reactor. At the HDPE reactor unit, ethylene is introduced into the reactor vessel as a gas (at a pressure condition between 1-20 atm) to react with the active site of the catalyst to produce polyethylene. Hexane is used as the solvent to dispel heat in the reactor. At the exit of the HDPE reactor unit, polyethylene is generated, which has melting point approximately 130 degrees Celsius. Hence, the polyethylene is formed in a solid state, which is called slurry

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[2] This chapter has been published in Journal of Material Cycle and Waste Management 2014; 16 (2) p.373-383.

polymerization or suspension polymerization. At the fractionators unit, hexane and un-reacted ethylene are separated from the polyethylene for reuse in the process again. Then polyethylene is recovered using the extruder and drying units. Finally, polyethylene is sent to pellet classifier unit and is ready for use at bulk product weight hopper unit.

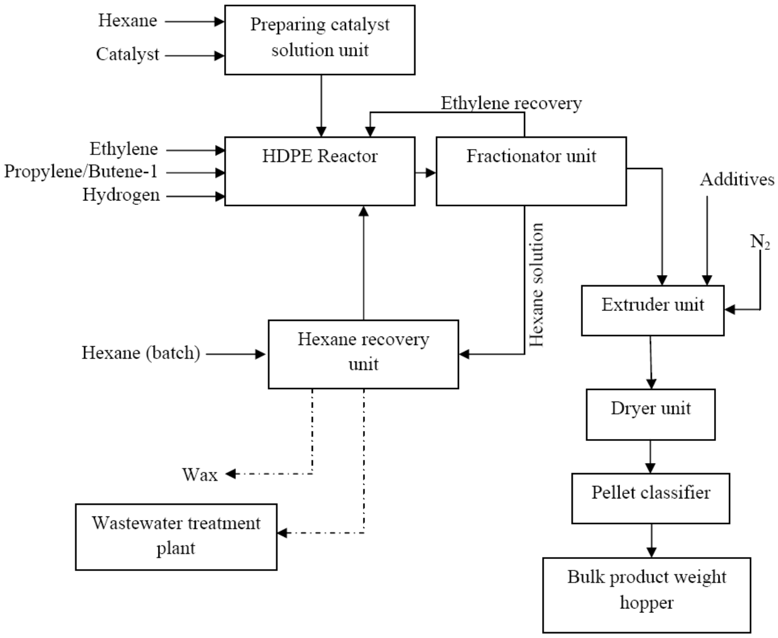


Figure 5.1 Simplified flow diagram of the HDPE production process of case study plants

5.2 Waste sources and types of wastes generation of the HDPE case study plant

The list of industrial-waste generated by the HDPE factory is presented in Table 5.1. The result indicated that 19 different kinds of industrial wastes were generated from the different activities of the factory, such as the production process, packaging & equipment, maintenance program, and waste treatment system. Some wastes-- viz. insulation, florescent tubes, contaminated containers, contaminated material, electronic waste, spent batteries, used oil, and oligomer--were determined to be hazardous waste, while the rest of all were classified as non-hazardous wastes.

Table 5.1 List of identified industrial-wastes in the HDPE factory

No.	Waste code	Identified waste item	Waste types	Waste categories
1	150101	Box/Packaging	Non-hazardous	Packaging & equipment
2	070213	Plastic scrap (powder and mass)	Non-hazardous	Production process
3	190814	Sludge from wastewater treatment plant	Non-hazardous	Waste treatment system
4	170603	Insulation	Hazardous	Packaging & equipment
5	160215	Fluorescent tube	Hazardous	Packaging & equipment
6	150110	Contaminated container	Hazardous	Packaging & equipment
7	150202	Contaminated material	Hazardous	Maintenance program
8	150203	Waste polymer	Non-hazardous	Production process
9	160213	Electronic waste	Hazardous	Packaging & equipment
10	160601	Spent battery	Hazardous	Packaging & equipment
11	130208	Used Oil	Hazardous	Maintenance program
12	070208	Oligomer	Hazardous	Production process
13	150102	Film Test	Non-hazardous	Packaging & equipment
14	150102	Gallon plastic	Non-hazardous	Packaging & equipment
15	170405	Iron scrap	Non-hazardous	Packaging & equipment
16	150103	Wood scrap	Non-hazardous	Packaging & equipment
17	150101	Paper scrap	Non-hazardous	Packaging & equipment
18	150102	Plastic pallet	Non-hazardous	Packaging & equipment
19	150104	Metal drum	Non-hazardous	Packaging & equipment

Figure 5.2 classifies the amount of wastes produced by the different activities of the plant based on the survey of the HDPE plant. From the survey found that, by weight, 47% was production process wastes, 46% was packaging & equipment wastes, 4% was treatment system wastes, and 3% was maintenance program wastes, respectively.

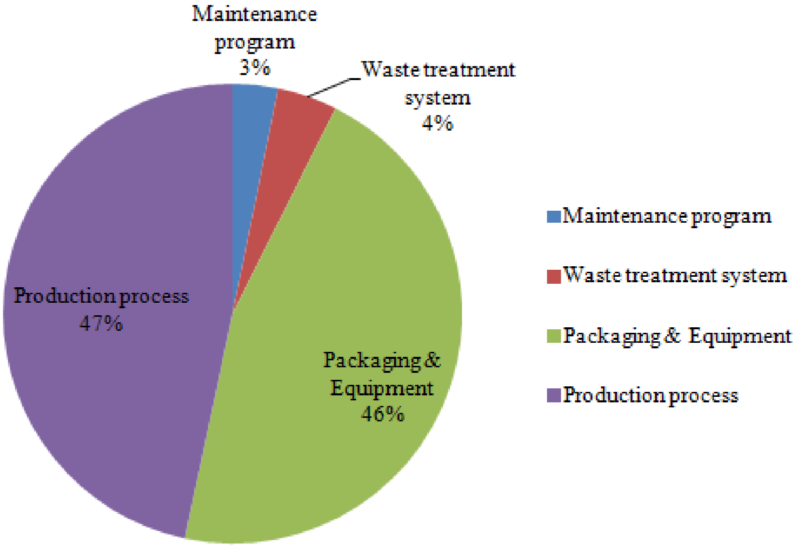
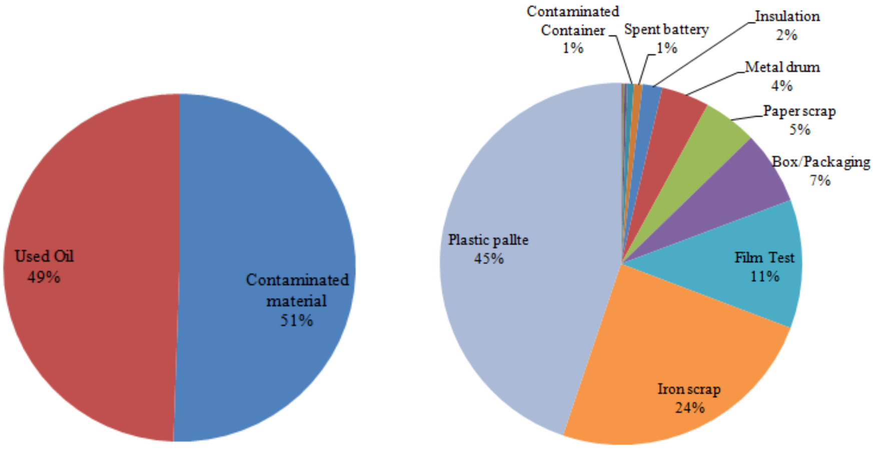
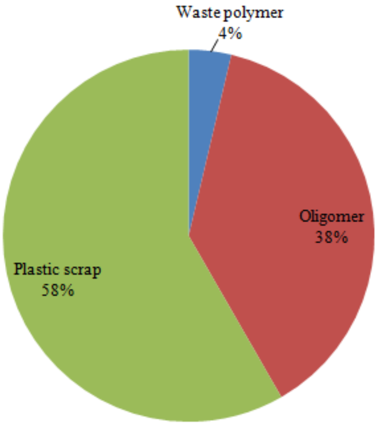


Figure 5.2 Wastes classification at the HDPE case study plant based on factory activities

Types of industrial wastes in each waste source were shown in Figure 5.3. In Figure 5.3a, it can be seen that maintenance activities produce used oil and “contaminated material”. In this study, the contaminated material being referred to is any material contaminated with oil and chemical substances. Most of the maintenance wastes are toxic or flammable, especially used oil. With regard to their management, these waste types can be burned for energy recovery, as their compositions have high heating values.



(a) Maintenance Wastes (b) Packaging & Equipment Wastes



(c) Production Process Wastes

Figure 5.3 Waste types from each factory activity of the HDPE petrochemical case study plant

In Figure 5.3b, it can be seen that there are nine types of packaging and equipment wastes: plastic palettes, iron scraps, film tests, boxes/packaging, paper scraps, metal drums, insulation, batteries, and contaminated containers. Wastes in this category are generated when those materials are damaged or out of service. Under the maintenance program, accidental leaks are the main causes of waste generation. Since most of packaging and equipment wastes are primarily composed of inorganic matter, they are unavailable for energy recovery treatments. Therefore, disposal of these wastes at a landfill is the first option.

In Figure 5.3c, production process wastes (e.g., plastic scrap, waste polymer, oligomer) are generated when the process cannot produce the plastic that meets the required specifications (as called “plastic off-spec”). The wastes from production process contain organic materials. Therefore, recycling and burning them for energy recovery can be applied for their management.

The wastewater treatment system was another source of industrial waste at this HDPE factory. However, the only type of solid waste it produced was sludge and landfill dumping is the most common method of managing sludge waste.

5.3 Existing waste management options

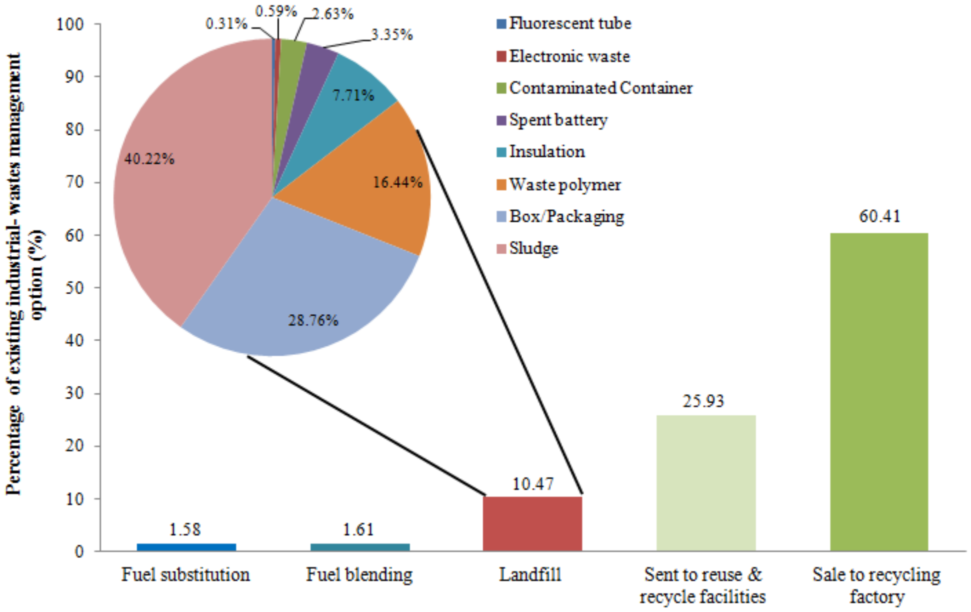


Figure 5.4 Existing waste management options for the HDPE case study plant and the waste types sent for landfill disposal

As can be seen in Figure 5.4, two main options are available to the HDPE plant: sales to recycling factory and sending material to reuse and recycling facilities. Due to most of their waste was plastic off-spec, it has valuable for selling to the recycling plastic factory or burning for energy recovery, yet there are some types of recyclable waste that are still being disposed of in a landfill.

In Thailand, the disposal of waste in a landfill site is common due to the site's low operation costs compared to that of the other options (incineration or recycling). However, landfill dumping has high environmental impacts: for instance, contamination of the soil can create long term problems in the groundwater system and affect human health and the environment. There are two types of landfill are as follows:

- Sanitary landfill is applied to the wastes or unused materials that are not hazardous waste, which may take the form of a solid or semi-solid, for example, sludge. Sanitary landfills must install leachate collection pipe system and also gas collection pipe system.

- Secure landfill is applied to the wastes or unused materials that are hazardous waste, which may take the form of a solid or semi-solid. Hazardous wastes must pass through the stabilization process before disposed of in a landfill sites. Secure landfill must install leachate collection pipe system and also gas collection pipe system.

From this survey it was determined that 10.47% (w/w) (57.29 tons) of the HDPE plant waste was sent to landfill, so it is important to reduce the amount of waste disposal by landfill and convert that waste by applying the 3R concept. The waste sent to landfill mainly consisted of sludge, boxes/packaging, waste polymer, insulation, spent batteries, and contaminated containers.

5.4 Proposed 3R options

Upon reviewing many publications and best practices, the list was narrowed down to which ones were to be applied at the plant, based upon their technical available and economic feasibility. The proposed 3R options can be classified into reduction, reuse/recycling options as shown in Figure 5.5. These options mainly aim to improve the waste management performance of the HDPE factory. Noted that recycling refers to the process of used materials or discarded material into new products, and may be used as a raw material or as a source of energy. Therefore, in this context thermal recovery was categorized in the recycling option.

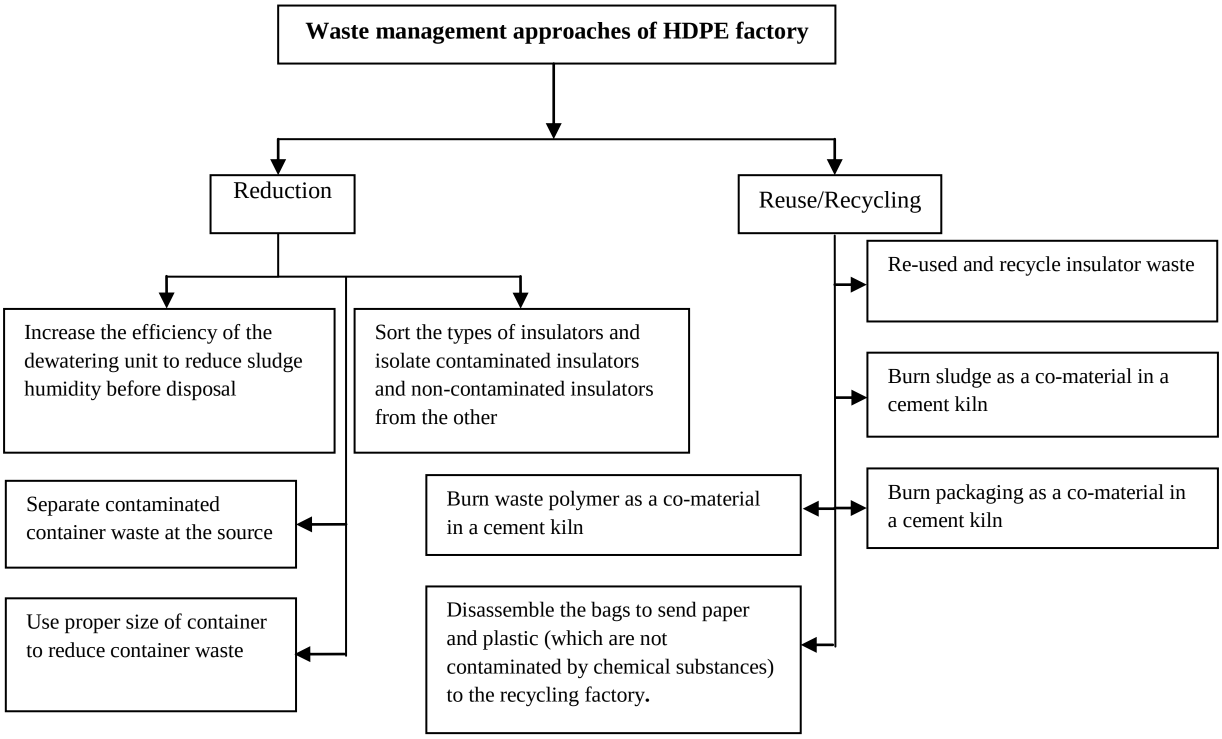


Figure 5.5 Proposed 3R options for improving waste management at the HDPE factory

5.4.1 Sludge from the wastewater treatment system

(1) Increase the efficiency of the dewatering unit to reduce sludge humidity before disposal

Sludge from wastewater treatment makes up a large portion of the waste that is sent to landfill. The one important method for reducing sludge waste at the source is increasing the efficiency of the dewatering unit, which can reduce the humidity of sludge before it is sent for disposal. Options for improving the dewatering unit are as follows:

- Improve the efficiency of the sludge conditioning process. A physical sludge conditioning method is known to generally improve sludge dewatering characteristics. This includes changing the floc structure so that it can be more compact form and reducing the sludge-bound water content (Buyukkamaci and Kucukselek, 2007).

- Good housekeeping of dewatering unit can improve is functioning and prevent the dewatering unit from malfunctioning. Moreover, inspections by the shift supervisor should be added before the dewatering unit is used (Usapein and Chavalparit, 2012).

(2) Burn sludge as a co-material in a cement kiln

Sludge has a heating value and can be incinerated to recover energy. When sludge is burned in a cement rotary kiln, the inorganic compositions in the sludge residues can be used as replacement materials in cement clinker (Monte et al., 2009). From the experiment, the heating value of sludge was 6.02 MJ/kg. With the quantity of sludge generated in 2010 (23.04 tons), it is estimated that the ideal energy can be recovered by burning is approximately 138,731 MJ/year.

5.4.2 Insulation waste

(1) Reduce and re-used insulator waste

Insulator was ranked fourth among the waste sent to landfill. It is generated in large volume during turnaround or maintenance at the petrochemical plant. Frequently, insulator wastes are contaminated by moisture, oil, and other chemical substances. The contaminants cannot be removed by available technology at the present. A surprising finding of the survey is that insulator wastes were not stored separately by type; in other words, contaminated insulator was not stored separately from non-contaminated insulator. Therefore, all of them needed to be disposed of by secure landfill as hazardous waste. Once the insulators are stored separately, the waste manager is able to select the proper disposal method for each type of insulator or even send the insulator for re-used.

5.4.3 Contaminated containers

(1) Separating waste at the source

Of first priority in the waste management hierarchy is reducing waste at the source. Sorting waste to prevent hazardous waste contaminating non-hazardous waste is the one promising method for reducing waste at the source. At the HDPE plant, waste containers were not classified and separated. All types of the contaminated containers were classified as hazardous waste and sent to landfill. To improve waste management system, the criterion of sorting waste process was established which based on the contamination and the packaging material. After sorting, container waste can be sold or donated as some of it is non-hazardous waste and can be re-used. Contaminated container wastes; for example, used tin cans (e.g. used paint cans, used thinner cans, catalyst containers) can be sent to a recycling processing plant instead of a landfill site. In addition, instead of being sent to landfill, plastic tanks can be shredded and then used as alternative fuel.

(2) Use proper size of container to reduce container waste

The proper selection of container products is important to reduce waste to landfill. The options of reducing container wastes are as follows:

- Use larger containers to reduce amount of packaging waste.
- Replace a liquid chemical with its powder form, to reduce the amount of packaging for transportation.
- Modify forms of packaging to easy for reuse. .
- Create a large waste container for the collection of waste, to reduce the use of small containers.

The environmental effects of selecting appropriate containers has been confirmed by (Rives et al., 2010); they report that the use of small HDPE containers was more detrimental to the environment than the use of a big steel container in terms of their Acidification Potential (AP), Global Warming Potential (GWP), Ozone Layer Depletion Potential (OLDP), and Abiotic Depletion Potential (ADP).

5.4.4 Waste polymer

(1) Burn waste polymer as a co-material in a cement kiln

Waste polymer generated from HDPE production process is classified as non-hazardous waste. The main composition of waste polymer is its organic content, which has a heating value; however, the present method for disposal is by landfill.

To increase the environmental benefits, therefore, it should be sent for use as an alternative fuel in a cement kiln instead.

5.4.5 Boxes/packaging

Packaging waste ranks second among the waste disposed of in a landfill by the plant. Packaging wastes include the waste bags used to contain the stabilizer (chemical substance) used to produce HDPE. Many types of stabilizers are used, which results in different kinds of waste bags. A summary of the types of stabilizers used and the resulting packaging is provided in Table 5.2.

Table 5.2 Types of stabilizer and the characteristics of the packaging waste

Type of Stabilizer	Characteristic of the packaging waste
HA Stabilizer	Waste bag that consists of 4 layers: (1) first layer (external layer) is a paper material (2) second layer is a paper material (3) third layer is a plastic material (4) fourth layer (internal layer) is a paper material contaminated with the stabilizer
AK stabilizer	Waste bag that consists of 3 layers: (1) first layer (external layer) is a paper material (2) second layer is a paper material (3) third layer (internal layer) is a plastic material contaminated with the stabilizer
UD stabilizer	Waste bag that consists of one layer of plastic material.
HC stabilizer	Waste bag that consists two layers of plastic material.
OB stabilizer	Waste bag that consists one layer of plastic material.
AL stabilizer	Waste bag that consists one layer of plastic material.

(1) Disassemble the bags to send the paper and plastic (that are not contaminated with chemical substances) to a recycling factory.

As shown in Table 5.2, HA stabilizer waste bags and AK stabilizer waste bags have paper and plastic layers that have not been chemically contaminated. If these layers are separated out, they can be sold back to a recycling factory. From a disassembly bag experiment, it was found that the recycling of these waste bags can reduce the amount of waste sent to landfill by approximately 0.2 kg/bag.

(2) Burn as a co-material in a cement kiln

Boxes and packaging waste were classified as hazardous waste because they were contaminated by stabilizers. The current disposal method is by secure landfill. However, another interesting method is to burn them as a co-material in a cement kiln. Burning hazardous waste for significant energy recovery and material recovery potential is valued over waste treatment. It is valued because it can reduce greenhouse gas emissions, the amount of wastes sent to landfill, and the environmental impacts on the ecosystem.

5.5 Implementation the selection of proposed 3R option

The 3R options were introduced to the case study factory in January 2011, and two options were selected to be applied: the burning of waste polymer and the burning of boxes/packaging as alternative fuels in cement kilns. These two practices were implemented from January to December 2011. Figure 5.6 shows that in 2010, the amount of waste disposed of in a landfill was estimated to be similar the following year if the selected 3R practices were not implemented. However, the amount of landfill waste disposal actually decreased by approximately 33.88%, after 3R options were applied.

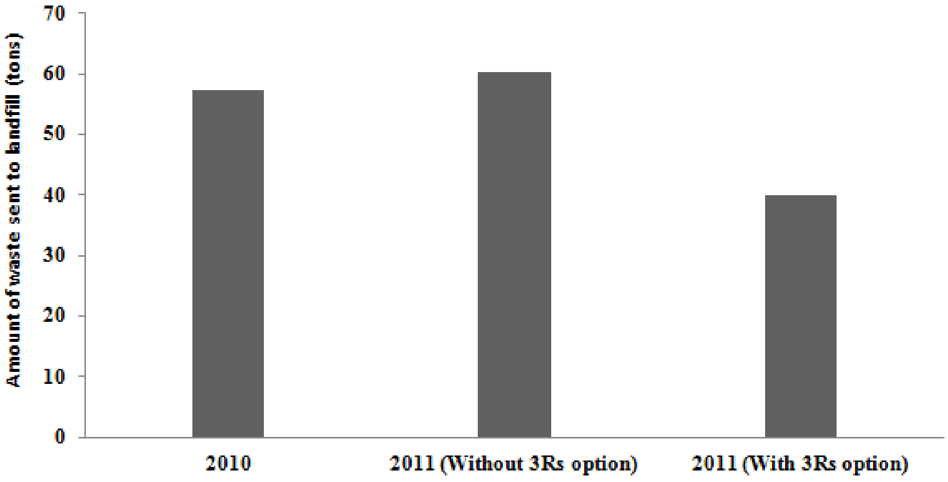


Figure 5.6 Annual waste disposed of at a landfill by the HDPE plant

5.6 Alteration of environmental impact and disposal cost

(1) Comparison the environmental impact of using waste as alternative fuel

Due to the selected options in this case study are the recycling options by burning waste polymer and box/packaging as co-material in cement kiln. Therefore, the environmental impact of burning waste compared with conventional fuel in cement kiln was evaluated. In this aspect, we need to confirm that burning waste as alternative fuel in cement kiln is a suitable option for environment. Therefore, the required energy (3,000 MJ) of producing 1 ton of clinker was used as functional unit (IPPC, 2001). The methodology of assessing environmental impact was based on Environmental Design of Industrial Products (EDIP) 2003 V1.03. The normalization and weighting factors were not applied in this study. The calorific value in each of fuel type was shown in Table 5.3. With different aspects, it should be noted that the result in this section will be different when compared with the result in Chapter 6. This is because the different of functional unit and methodology for assessing environmental impact.

Table 5.3 The calorific value of fuels

Type of fuels	Calorific value (MJ/ton)	Amount of fuel for producing 1 ton of clinker	Unit
Bituminous (coal)	23,865[a]	0.13	ton of bituminous /ton of clinker
Waste polymer	43,000[b]	0.07	ton of waste polymer /ton of clinker
Kraft paper	16,890[c]	0.18	ton of kraft paper /ton of clinker

[a] (UNFCCC, 2013)

[b] (Sarker et al., 2011)

[c] http://www.deq.state.or.us/lq/pubs/docs/sw/packaging/LifeCycleAppendixE.pdf

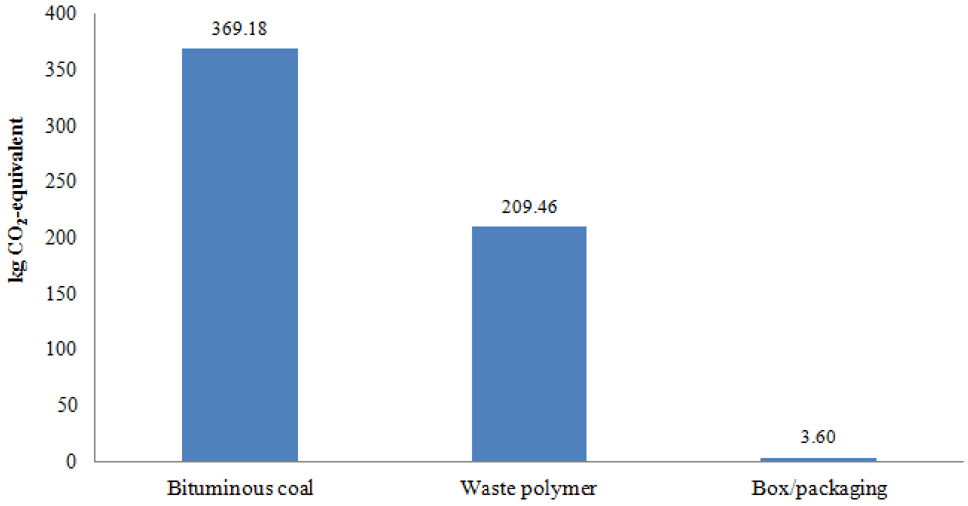


Figure 5.7 Comparison GHG emission of using waste as alternative fuel with conventional fuel

As shown in Figure 5.7, the GHG emission of using bituminous coal for producing one ton of clinker was the highest, followed by waste polymer, and box/packaging. Although the required amount of box/packaging for producing one ton of clinker was the highest, the impact of GHG emission was the least. From the result, it can be explained that the boundary of calculating GHG emission of using bituminous coal was different from the two others (as shown in Figure 5.8).

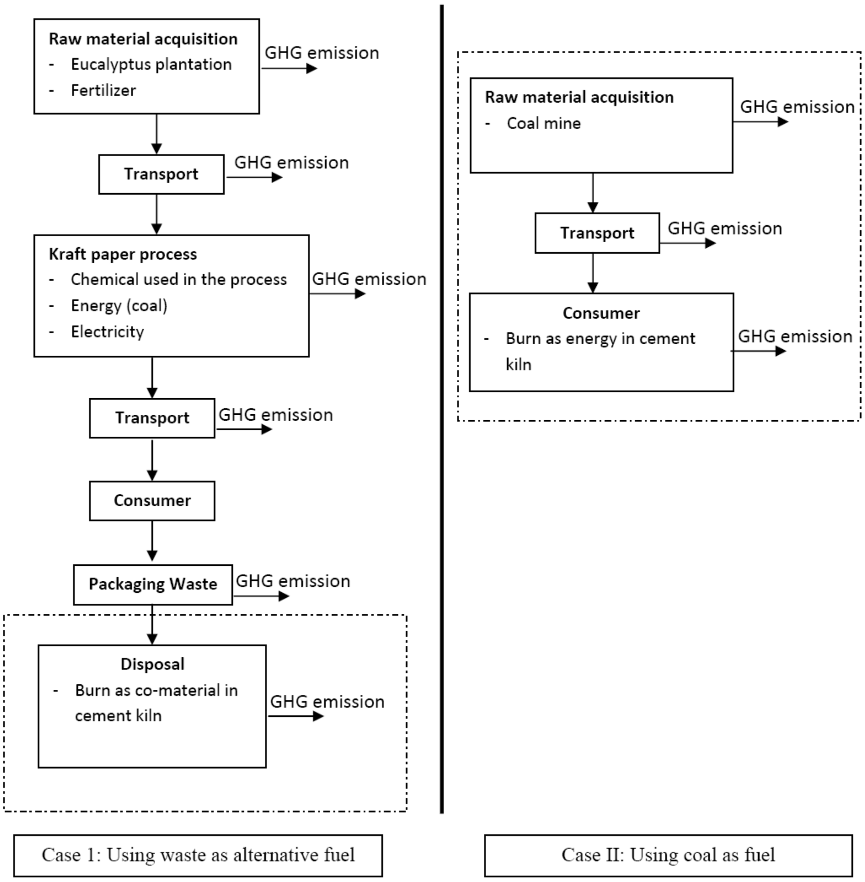


Figure 5.8 System boundary of calculating environmental impact

In case of using bituminous coal, the GHG emission during raw material acquisition and coal production were included, while the two others were not. In addition, GHG emission of box/packaging was the lowest because the main composition of box/packaging was consisted of kraft paper which can be easily converted to the energy by using lower energy consumption than the other fuel types. Furthermore, the trends of other environmental impact were similar to GHG emission as shown in Table 5.4.

Table 5.4 The environmental impact of using waste as alternative fuel compared with conventional fuel

Impact category	Unit	Bituminous coal	Waste polymer	Box/packaging
Ozone depletion	kg CFC11 eq	4.64E-06	7.96E-08	2.65E-07
Acidification	m^2	47.66	0.26	0.86
Aquatic eutrophication EP(N)	kg N	0.08	0.003	0.01

(2) Cost comparison of waste disposal methods

The cost of waste disposal was collected by site visit at the HDPE case study plant in Thailand (personal communication, June 1, 2011). As can be seen in the Table 5.5, the total cost of disposal waste polymer by cement kiln (5,940 baht) was higher than landfill (2,420) and this result was similar to cost of disposal box/packaging (63,700 baht of cement kiln; 54,600 baht of landfill). Cost of disposal in each type of wastes depended on the characteristics of waste such as heating value, hazardous or non-hazardous, and quantity. In case of disposal by cement kiln, wastes that have high heating value tend to be disposed by lower price. While landfill has normally cost of waste disposal cheaper than cement kiln, the cost of landfill might be increased when wastes have a characteristic as hazardous waste and formed in liquid state.

Table 5.5 Cost of waste disposal

Type of wastes	Quantity (tons)	Landfill (baht/ton)	Cement kiln (baht/ton)
Waste polymer	2.20	1,100	2,700
Box/packaging	18.20	3,000	3,500

5.7 Conclusion

This research has applied 3R concept to improve industrial waste management at a Thai high-density polyethylene (HDPE) plant. A comprehensive 3R methodology was used to (1) identify the types of wastes, (2) identify the existing waste management practices, (3) propose feasible 3R practices, and (4) implement the selected 3R practices. In this study, we recommend that the framework of operating 3R project should be followed as shown in Figure 5.9.

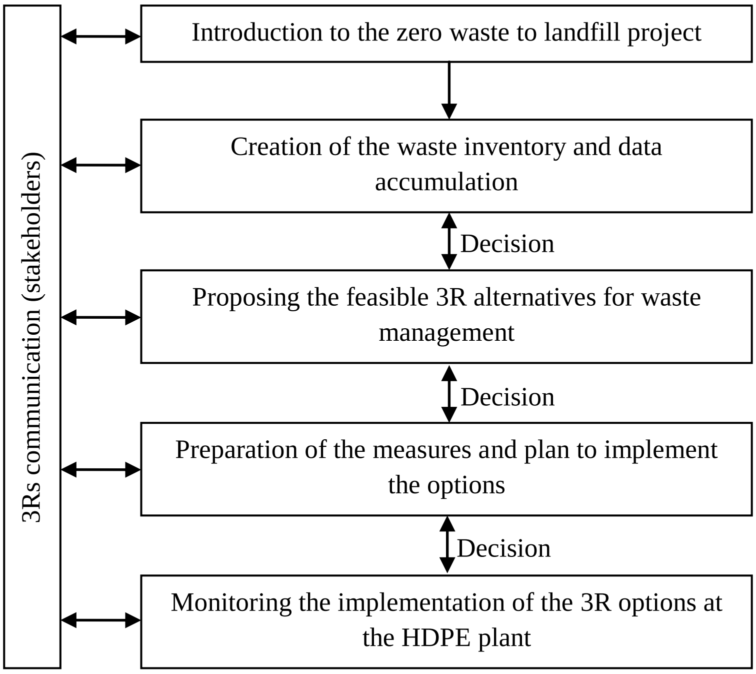


Figure 5.9 Framework of the proposed 3R options for the HDPE case study plant

The results can be concluded in the following passage. Four sources of waste generation are identified: (1) production, (2) packaging (3) wastewater treatment, and (4) maintenance, distributed as 47%, 46%, 4%, and 3%, respectively. The main waste management options are sale and sent to recycling factory; nevertheless, landfill method was still used by the HDPE plant. The 3R practices followed a waste hierarchy approach, which prioritized the 3R's (reduce, reuse, and recycle), in order to minimize waste generation and environmental impacts. The implementation of the selected 3R options over the course of one year was able to decrease wastes sent to landfill by 33.88% (w/w). However, some waste type such as insulation, sludge, and contaminated containers still needed to be disposed of in a landfill. In the case of insulation, most of the insulation waste was rock wool insulation, and as of yet, Thailand does not possess the technology to recycle this type of waste. For sludge, landfill disposal was selected over the cement kiln burning due to its economic feasibility. In case of changing in environmental impact, when using waste as alternative fuel in cement kiln both waste polymer and boxes/packaging show better environmental impact than bituminous coal. Therefore, we believe that diverted waste from landfill to burn as an alternative fuel is a good choice for improving waste management system of HDPE plant. It can conserve resources and reduce emission to air. However, the things should be concerned that not every types of waste are suitable to burn; therefore, the first awareness of the HDPE plant should try to start from reduction waste at source and reuse as much as possible. Although the last R (Recycling) will benefit the environment, it also emits the pollutant from the process to the environment.

CHAPTER VI

ENVIRONMENTAL IMPACT ESTIMATION OF ALTERNATIVE WASTE MANAGEMENT OPTIONS FOR PETROCHEMICAL WASTES

In the previous chapter we showed the effective of 3R concept applied with petrochemical plants. The results showed that 3R methodology has high potential for reducing landfill wastes. However, the result is not clear in term of environmental impact. Therefore, the objective of this chapter is to assess the environmental impact of alternative options for managing petrochemical wastes from petrochemical industry in Thailand. The scenarios, such as reuse option, recycling option, landfill option, cement kiln option, and co-composting option, were selected to evaluate the impact of Global Warming Potential (GWP), Acidification Potential (AP), Terrestrial Acidification and Nitrification (TAN), Aquatic Eutrophication Potential (AEP), Aquatic Ecotoxicity (AE), Terrestrial Ecotoxicity (TE), Non-Carcinogenic Effects, and Carcinogenic Effects. The results are expected to use as a tool for decision making of disposing petrochemical wastes.

6.1 Life Cycle Assessment (LCA) methodologies

6.1.1 Goal and Scope

The objective of this study was to identify the most environmentally friendly option for disposal petrochemical waste.

(1) Functional unit: The definition of the functional unit for each option was based on 1 ton of industrial waste. The data, such as emissions, energy consumption, chemical reagent, and materials, were based on this functional unit.

(2) System boundary**:** The environmental impact was emphasized on waste disposal technology which covered products from waste treatment and its environmental impact for such activity as presented in Figure 6.1. The emissions

related with plant constructions (landfill site, cement plant, recycling plant, and fertilizer plant) were determined as insignificant and could negligible in this study.

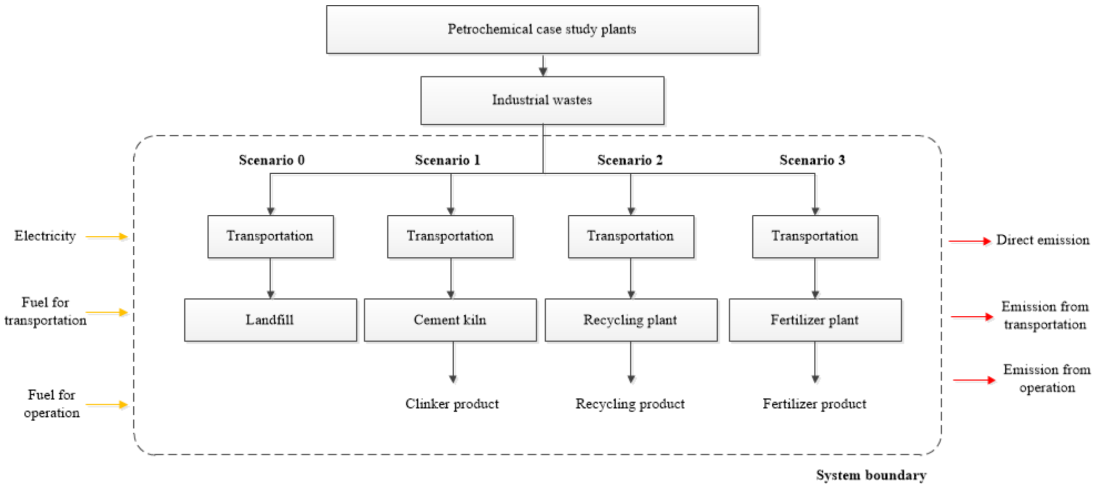


Figure 6.1 System boundary of the study

In this chapter, the environmental impact of waste disposal will be shown in each type of landfill waste. All landfill wastes were used the same system boundary. The alternative options applied for landfill waste as scenario depend on its chatacteristics of landfill waste. The details of data source and environmental impact of each landfill waste type are provided below.

6.1.2 Data source and life cycle inventory analysis

Sludge from the activated sludge wastewater treatment system

Sludge was sampling at petrochemical case study plant, Rayong province, Eastern of Thailand. The composition of sludge was analysed by CHNS/O elemental analyser (as shown in Table 6.1). The concentration of heavy metal in sludge was analysed by Inductively Coupled Plasma (ICP). The landfill gases were estimated based on theoretical anaerobic decomposition, and using correction factor available from the literature. The capability of electricity production from sludge was based on the data of chemical sludge characteristic and the efficiency of the gas engine generator. In this study, sludge was analyzed the heating value by bomb calorimeter machine. Data emission output on fertilizer production were obtained from the previous research (Arworn and Chavalparit, 2012). Data from Thailand were used as a main source when available. In case of these data were not available, the database from European were used (EcoinventCentre, 2007).

Table 6.1 Properties of sludge from the petrochemical plant.

Proximate analysis	**Value**	**Unit**
Moisture content [a]	90	%
Heating value	18.5	MJ/kg
Volatile solid	77.0	%
Ash	20.4	%
Ultimate analysis		
%C	44.2	%
%H	6.30	%
%O	39.8	%
%N	6.26	%
%S	3.40	%
Heavy metal		
Cd	6.1	mg/kg
Cr	190	mg/kg
Hg	13.2	mg/kg
Pb	54.6	mg/kg
Ar	6.5	mg/kg
Cu	62	mg/kg

[a] In wet matter basis.

Copper slag

The composition of copper slag consists of ferrous oxide (55%), alumina oxide (3.01%), and silica oxide (35%) (Star-Grit, 2009). The inventory data of this waste type was obtained from Eco-invent database.

Refractory brick

Refractory brick was consisted of an aluminium oxide which can be up to 50-80% (Vitcas, 2011). The inventory data of this waste type was obtained from Eco-invent database.

Contaminated container

Contaminated container from petrochemical case study plant consisted of various material types, for example, High density polyethylene (HDPE), Polystyrene (PS), metal can, and etc. In this study, however, HDPE container as main type of container were selected to evaluate the environmental impact from alternative waste management options. The inventory data of HDPE were obtained from Eco-invent database.

6.2 Scenario analysis

6.2.1 Sludge from the activated sludge wastewater treatment system

The boundary of calculated environmental impact was shown in Figure 6.2. Sludge from petrochemical case study plant has three alternative waste management options such as landfill with electricity production, cement kiln, and fertilizer plant.

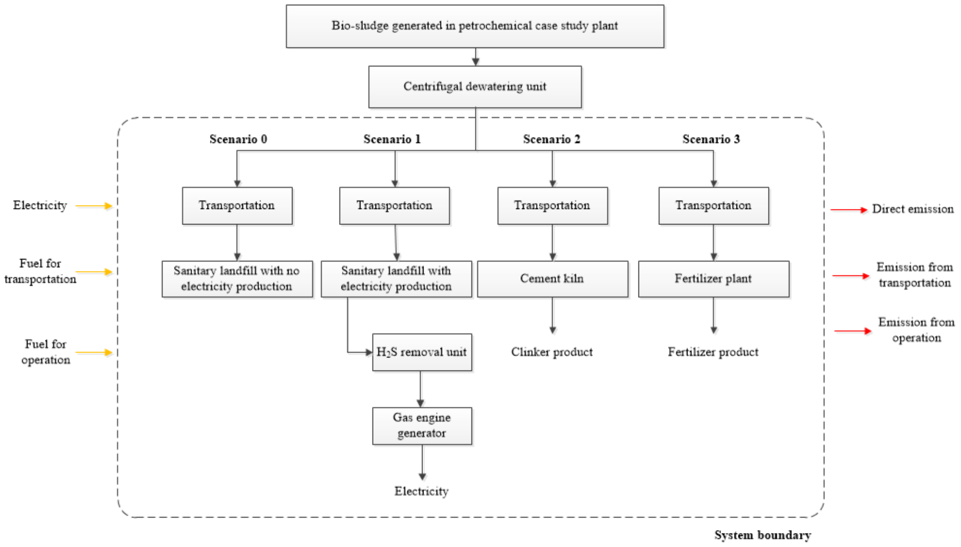


Figure 6.2 System boundary of sludge waste management

The emission of raw material, transport, energy consumption, direct emissions, and waste disposal, to the environment were evaluated in each scenario. Table 6.2 illustrates a summary of LCI data for disposal of 1 ton of bio-sludge in each scenario. The detail in each scenario can be explained as follows:

Table 6.2 Emission inventories in selected parameters of each scenario (per ton of sludge).

Scenario	Emissions		Values	Unit
Landfill	Emissions to air	CH_4	177	kg
		CO_2	717	kg
		NH_3	55.1	kg
		H_2S	27.5	kg
	Emissions to water	COD	33.1	g
		SS	41.4	g
		T-N	55.2	g
		T-Hg	0.0014	g
		T-Cr (III)	0.2070	g
		T-Cr (VI)	0.0690	g
		T-Cd	0.0083	g
		T-Pb	0.0552	g
		T-As	0.0690	g
Cement kiln	Emissions to air	CO_2	1,619	kg
		NO_x	194	kg
		SO_2	67.3	kg
		As	1.30	mg
		Cd	3.05	mg
		Cr	22.8	mg
		Cu	5.77	mg
		Hg	6,600	mg
		Pb	27.3	mg
	Emissions to water[a]	COD	9.88	kg
		SS	1.48	kg
		NH3-N	998	g
		T-Hg	0.0217	g

Scenario	Emissions		Values	Unit
		T-Ni	0.7100	g
		T-Cr	0.8500	g
		T-Cu	0.2100	g
		T-Pb	0.3800	g
		T-Fe	30.3	g
		T-Mn	0.9100	g
Fertilizer option	Emissions to air[b]	CH_4	6.40	kg
		N_2O	0.2181	kg
		NH_3	1.01	kg
	Emissions to water[b]	NO_3^-	33.0	kg
	Emission to soil[c]	Organic carbon	205	kg
		T-N	10.9	kg
		T-P	6.50	kg
		T-K	3.70	kg
		As	2.48	g
		Cd	0.5100	g
		Cr	21.0	g
		Cu	22.0	g
		Hg	1.11	g
		Pb	3.50	g

[a] (Hong et al., 2010)

[b] (Cederberg, 2004; Flodman, 2002)

[c] (Arworn and Chavalparit, 2012)

Landfill (Scenario 0)

After organic material disposed of in landfills, the organic material will be degraded in anaerobic condition. In this study, we assumed that the conversion of organic waste (bio-sludge) to produce CH_4, CO_2, NH_3, and H_2S gases was following the stoichiometry equation (6.1). The original stoichiometry has introduced by (Tchobanoglous et al., 1993). In this study, however, we have modified the stoichiometry equation due to sulfur content in sludge cannot be neglected.

$$8C_{35}H_{59}O_{24}N_4S + 94\ H_2O \rightarrow 137CH_4 + 32NH_3 + 143CO_2 + 8H_2S \qquad (6.1)$$

From the equation 6.1, the molecular weight of sludge was estimated about 951 g/mol. As shown in Table 1, sludge contains 77% of volatile solid which will be completely converted to landfill gas. Four components of landfill gas (e.g. CH_4, NH_3, CO_2, and H_2S) were confirmed that it occurs on landfill sites from the previous studies (Plaza et al., 2007; Themelis and Ulloa, 2007). In this scenario, landfill site was assumed to install the passive venting system; the efficiency of landfill gas collection was only accounted 40% of total landfill gas generation. The uncollected landfill gas will be stayed in the landfill and leaked to the environment in finally. For actual CH_4 leakage from landfill, some part of methane leakages will be oxidized by soil; the percentage of soil oxidation was varied in the range of 40-60% (Kightley et al., 1995). This study, 60% of the uncollected methane was assumed to be oxidized by soil while 40% of the uncollected methane will be directly leaked to the environment. In case of H_2S, based on the study of Plaza et al. (2007), we assumed that 70% of the uncollected hydrogen sulfide will be emitted to the environment, while 30% of the uncollected H_2S will be sorption and conversion to metal sulfide minerals in soil. Landfill site location is at Radchaburi province, Thailand. The transportation distance from wastewater treatment system at petrochemical case study plant to landfill site was 323 km.

For emission to water, the standard for industrial wastewater standards in Thailand according to the Notification of the Ministry of Science, Technology and Environment, No.3, A.D. 1996 (MSTE, 1996) was used to assess the environmental impact from leachate emission.

Landfill with landfill gas utilization by producing electricity (Scenario 1)

In this scenario, the efficiency of landfill gas collection was varied in the range of 40-90%. The collected landfill gas will be treated by wet scrubber with the efficiency of 90% H_2S removal (Chen et al., 2006) before burning in electric generator to produce electricity. The residue of landfill gas, which still contained in landfill (uncollected), were considered as environmental impacts from Scenario 1, and include gas combustion from electric generator. The efficiency of gas engine generator for producing electricity was assumed to be 40% (Cuéllar and Webber, 2008).

Use of bio-sludge as a conventional fuel substitute in cement kiln (Scenario 2)

This scenario sludge was mixed with lignite coal and then incinerated in cement kiln at the temperature of 2000°C. After sludge was burned, the resultant sludge ashes would be combined into the clinker product and not necessary to disposed of in landfill sites (Husillos Rodríguez et al., 2013). The characteristic of sludge ashes was shown in Table 6.3. Based on the heating value of sludge, one ton of bio-sludge can be used to substitute the amount of lignite coal for 1.23 ton. The exhaust gas of clinker process will be passing through desulfurization process with 90% of capturing sulphur dioxide (EPA, 2003). Due to lack of information data on heavy metal emission from cement kiln in Thailand, the heavy metal emission was calculated based on transfer-coefficient for co-incineration in cement manufacturing which obtained from the study of (Lederer and Rechberger, 2010). Cement factory in this scenario was located at Saraburi province, Thailand. Distance between petrochemical plant and cement factory was 321 km.

Table 6.3 Characteristics of sludge ashes.

The percentage (%) of elements (w/w)								
Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2
11.82	0.61	1.90	9.60	6.62	39.82	0.78	2.69	0.10
Cr_2O_3	MnO_2	Fe_2O_3	NiO	CuO	ZnO			
0.19	0.23	22.27	0.08	0.05	1.38			

Recycling bio-sludge as raw material for fertilizer production (Scenario 3)

According to the previous study, sludge would be mixed with other highly fermentable organic wastes to adjust organic carbon content and humidity for optimizing condition of the compostable mixture (Tarantini et al., 2007). The methodology of composting bio-sludge as a co-material to produce fertilizer was gathered the data from (Arworn and Chavalparit, 2012). This study, bio-sludge was composted by mixing with sawdust and microbial inoculums. The compostable mixture is feed into the composting reactor with forced aeration for the bio-oxidation. The yield of fertilizer production is about 0.2 ton fertilizer/ton of sludge. Due to lack of data availability, the direct emissions from the process were based on the value that available from literature (Cederberg, 2004; Flodman, 2002). Fertilizer factory is located at Rayong province, Thailand; its 105 km away from petrochemical case study plant.

6.2.2 Copper slag

Landfill (Scenario 0)

In this study, copper slag was assumed to dispose of by a residual material landfill without solidification. The landfill site was assumed to locate at Radchaburi province, Thailand; its 323 km away from the petrochemical case study plant. The diesel fuel for transportation is 6.73 lit/ton waste.

Use of copper slag as a co-material in cement kiln (Scenario 1)

In case of burn as co-material in cement kiln, we assume to use the data of process-specific burdens, slag compartment from Eco-invent database. The cement kiln was assumed to locate at Saraburi province, Thailand; its 321 km away from the petrochemical case study plant. The diesel fuel of transportation is 6.69 lit/ton waste.

6.2.3 Refractory brick

Landfill (Scenario 0)

Refractory brick was assumed to dispose of in a residual material landfill which need to solidification with cement before added to landfill site. The distance of landfill site was 321 km away from the case study plant. The fuel consumption is 6.69 lit/ton waste.

Use of refractory brick as a co-material in cement kiln (Scenario 1)

The detail of this scenario is assumed to be the same of burn copper slag in cement kiln (see in section 6.2.2).

6.2.4 Contaminated container

Landfill (Scenario 0)

High density polyethylene (HDPE) was assumed to be disposed of by landfill site. The inventory data of direct emission from landfill were obtained from Eco-invent database. The detail of transportation was the same with landfill site in case of copper slag (see in section 6.2.2).

Reuse contaminated container (Scenario 1)

To reuse container, it need to clean up before re-use for an application. The data of treated water and electricity consumptions were obtained from (Rives et al., 2010). To reuse 1 ton of contaminated container, 30.56 m^3 of water and 1456.25 MJ of electricity were used to clean up (Rives et al., 2010). The avoided of HDPE product were calculated 1 ton per ton of reuse contaminated container.

Send to recycling factory (Scenario 2)

In this scenario, we assumed that HDPE containers were sent to recycle at the plastic recycling plant. The data of recycling plastic process was obtained from (Perugini et al., 2005). To recycling 1 ton of HDPE container waste, 1561 kg of water, 526.3 MJ of methane, and 1754 MJ of electricity were used as auxiliary material and energy. The efficiency of reprocessing HDPE plastic was assumed to be 88%. The residue of recycling process was disposed of by landfill. The distance of recycling plant was 151 km away from the case study plant. The fuel consumption is 3.15 lit/ton waste.

6.3 Impact assessment

The environmental impact from each scenario was calculated at mid-point and damage level using IMPACT 2002+ method. Nine mid-point impacts were selected in this study such as: the impact of Global Warming Potential (GWP), Acidification Potential (AP), Respiratory Inorganic (RI), Terrestrial Acidification and Nitrification (TAN), Aquatic Eutrophication Potential (AEP), Aquatic Ecotoxicity (AE), Terrestrial Ecotoxicity (TE), Non-Carcinogenic Effects, and Carcinogenic Effects. These mid-points will be linked to three damage categories (human health, ecosystem quality, climate change) to compare each option of waste disposal.

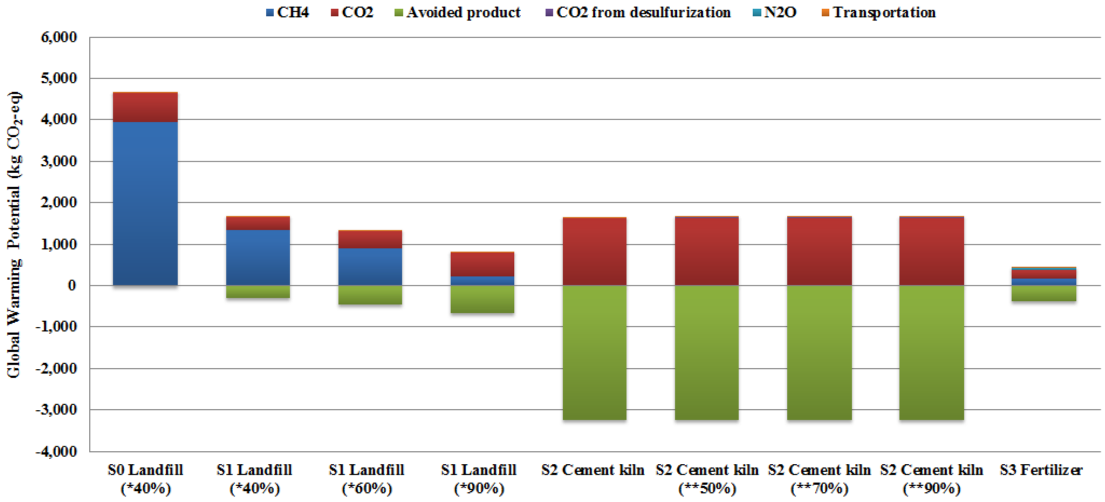
6.4 Interpretation

The results of impact assessment section from alternative waste management options were interpreted in order to compare the environmental performance.

6.5 Mid-point characterization result

6.5.1 Sludge from the activated sludge wastewater treatment system

(1) Estimation Global Warming Potential (GWP) of each scenario



* The efficiency of methane gas collection

** The efficiency of desulphurization unit

Figure 6.3 Global Warming Potential (GWP) of each sludge scenario.

The results of the CO_2-eq emission in different scenarios were presented in Figure 6.3. Among the investigated scenarios, scenario 0 was shown the greatest GWP with the total emission of 4,686 kg CO_2-eq, followed by scenario 1 (1,685 kg CO_2-eq), scenario 3 (86 kg CO_2-eq) and scenario 2 (-1,597 kg CO_2-eq). Scenario 0, the anaerobic digestion in landfill was a main source of GWP, which some part of landfill gases were directly released to the environment. GWP resulted from the anaerobic mechanism in landfills were composed of two gas types, such as CH_4 and CO_2. Methane gas can break down faster than carbon dioxide; therefore, it adding more negative impact on global climate. For scenario 1, although CH_4 was collected and used to produce electricity, there was still some outstanding CH_4 in the landfill; and leaked into the environment as a main part of the bulk of CO_2 emissions into the atmosphere from landfill. In scenario 2, GWP was strongly CO_2 emission by the combustion of sludge. The GWP of bio-sludge incineration was much higher than the direct impact from fertilizer option. When determine the impact from avoided product, it was found that cement kiln option shows higher potential in GWP reduction than fertilizer option.

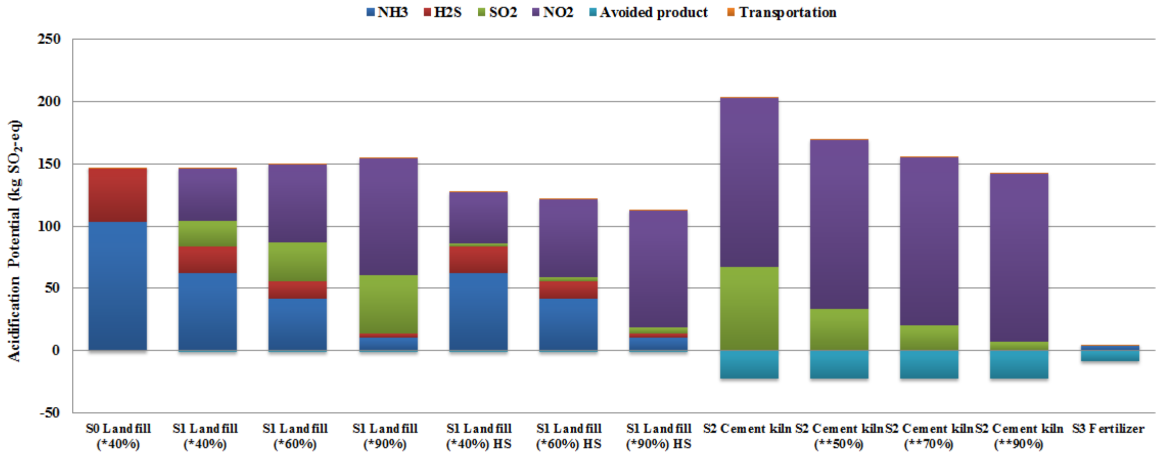
A sensitivity analysis of the methane collection efficiency in scenario 1 was evaluated. The result revealed that the efficiency of methane collection system is an important factor to control GWP in scenario 1. The better methane collection system can show significant in GWP reduction.

In case of scenario 2, the sensitivity analysis of wet scrubber efficiency was considered. To remove sulfur dioxide in exhaust gas, wet scrubber was applied; the reaction to extract sulphur dioxide was assumed to be as equation 6.2:

$$SO_2 + 0.5H_2O + CaCO_3 \rightarrow CaSO_3.0.5H_2O + CO_2 \qquad (6.2)$$

As shown in Figure 6.3, the result indicated that the efficiency of wet scrubber is not significant change in greenhouse gas emission because the CO_2 emission is generated in small quantities.

(2) Estimation Acidification Potential (AP) of each scenario



* refers to the efficiency of methane gas collection.

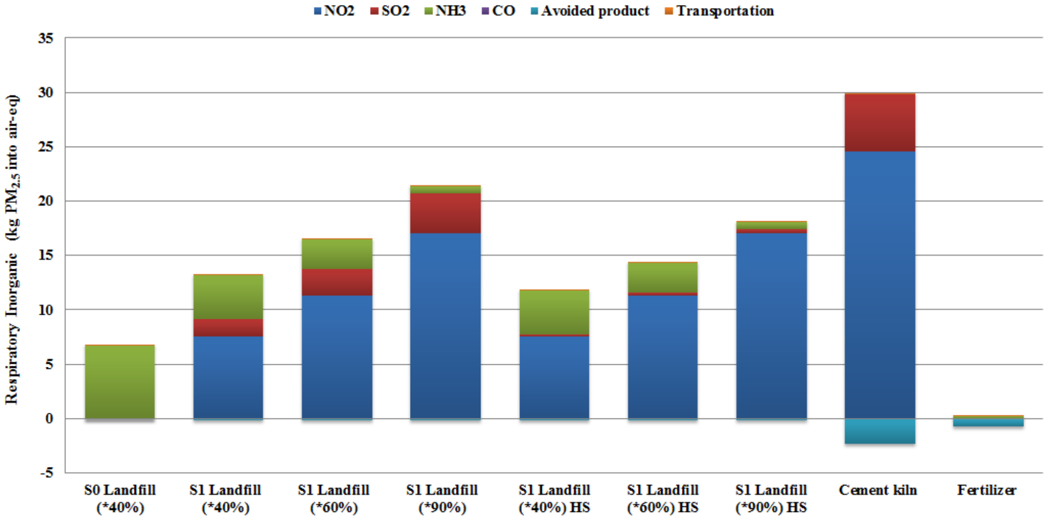
** refers to the efficiency of desulphurization unit.

HS refers to the efficiency of hydrogen sulfide removal (90%).

Figure 6.4 Acidification Potential (AP) of each sludge scenario.

The calculated AP of each scenario was shown in Figure 6.4, expressed as kg SO_2-eq. It was observed that scenario 2 was highest total AP at 180.41 kg SO_2-eq., while fertilizer was lowest total AP at -4.59 kg SO_2-eq. In Scenario 2, the main SO_2 emissions were derived from NO_x and SO_2 during sludge combusted in cement kiln. In typical situation, however, sulphur dioxide gas must be removal by wet scrubber before discharge gas to the environment. Therefore, a sensitivity analysis of sulphur dioxide removal efficiency was evaluated. The result indicated that the efficiency of SO_2 removal is an important role for AP reduction. Although the efficiency of SO_2 removal could affect to increase the CO_2 emission according to the stoichiometry equation (6.2), the result in Figure 6.3 proves that the effect has no significant in GWP increase. In case of scenario 1, the collected landfill gas was passing through wet scrubber to remove hydrogen sulfide. The residue hydrogen sulfide after treated landfill gas will be burned and converted to sulfur dioxide. When 90% of hydrogen sulfide removal was operated, the 90% of collected landfill gas was shown lowest AP. Therefore, it could be recommended that landfill gas should be treated H_2S before combusted in gas engine generator to reduce acidification potential.

(3) Estimation Respiratory Inorganic (RI) of each scenario



* refers to the efficiency of methane gas collection.

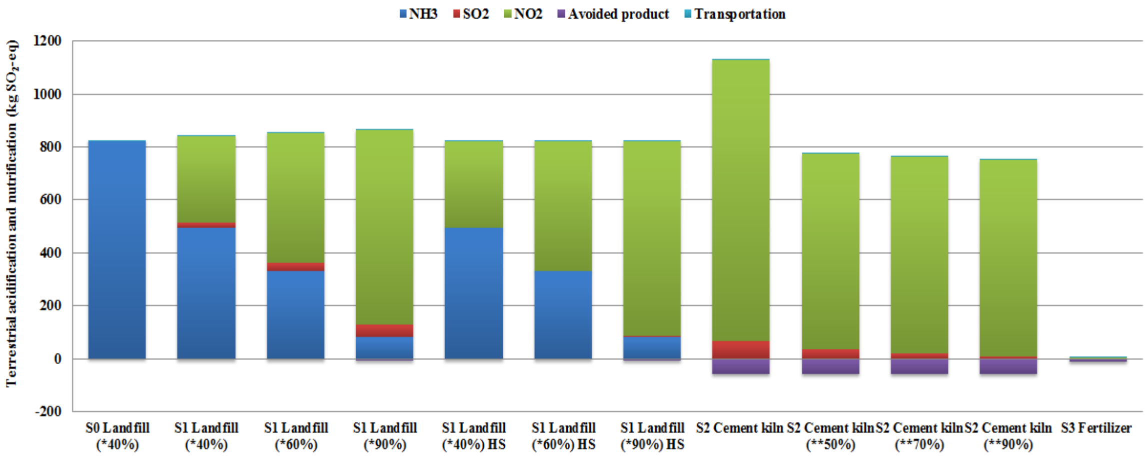
HS refers to the efficiency of hydrogen sulfide removal (90%).

Figure 6.5 Respiratory Inorganic (RI) of each sludge scenario.

Respiratory Inorganic (RI) of each scenario is shown in Figure 6.5. The highest impact of this category was occurred in scenario 2; in which NO_2 dominate over SO_2 pollutant. Scenario 3 was shown the lowest of RI, while scenario 0 has emitted largely ammonia gas as a pollutant of RI. However, the interesting point is occurred in scenario 1. When the efficiency of methane collection was increased, the impact of RI was also increased. This is because NH_3 was converted to NO_2 by landfill gas combustion in electric engine; furthermore, more H_2S was converted to SO_2 as well. Although the H_2S treatment unit was installed, the trend of increasing RI still high with the increasing of methane collection efficiency.

(4) Estimation Terrestrial Acidification and Nitrification (TAN) of each scenario

Terrestrial acidification and nutrification (TAN) of different scenarios, expressed as kg SO_2-eq, are demostrated in Figure 6.6. The highest value in this impact category was occurred in scenario 2 where NO_2 is a dominating pollutant from combusting sludge. The TAN impact of different options can be ordered as following: scenario 2 > scenario 1 > scenario 0 > scenario 3.



* refers to the efficiency of methane gas collection.

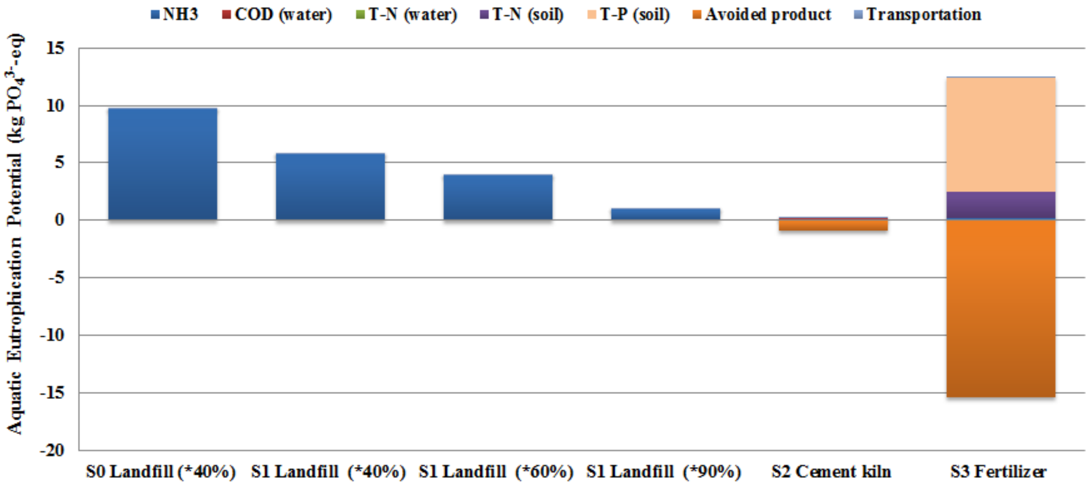
** refers to the efficiency of desulphurization unit.

HS refers to the efficiency of hydrogen sulfide removal (90%).

Figure 6.6 Terrestrial Acidification and Nutrification (TAN) of each sludge scenario.

The sensitivity analysis of SO_2 removal efficiency was also evaluated in scenario 2. From the result in Figure 6.6, the installation of desulfurization unit can reduce this impact by SO_2 removal from the exhaust gas. However, the sentivity analysis showed that there is no significant potential for TAN reduction with the efficiency of desulfurization unit; this result is similar with landfill option.

(5) Estimation Aquatic Eutrophication Potential (AEP) of each scenario

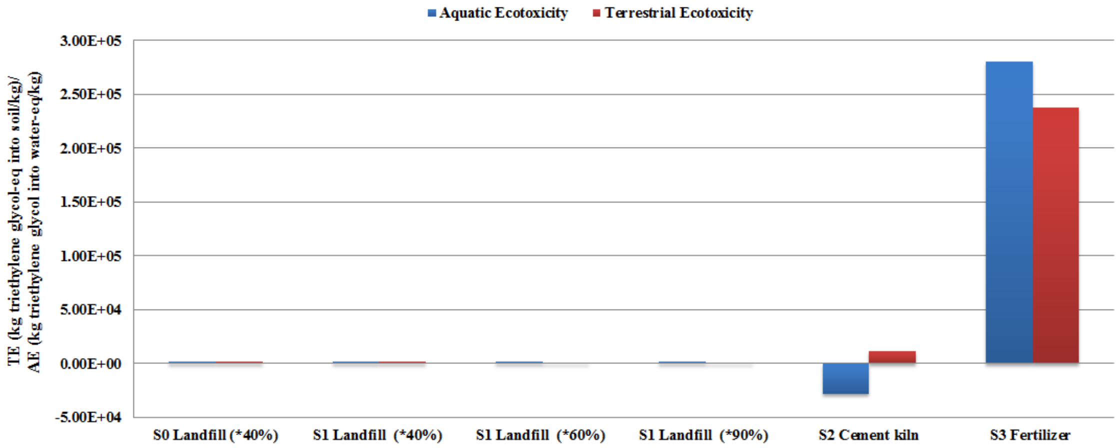


* refers to the efficiency of methane gas collection.

Figure 6.7 Aquatic Eutrophication Potential (AEP) of each sludge scenario.

Figure 6.7 shows the Aquatic Eutrophication Potential (AEP), expressed as kg PO_4^{-3}, derived from different scenarios. Different conclusions could be drawn from the results of GWP and AP analyses, in which the fertilizer option (scenario 3) was the greatest direct impact, followed by scenario 0, 1, and 2, respectively. The main contribution of AEP was emitted to soil by total phosphorus and total nitrogen. Scenario 1 emitted ammonia gas as a major pollutant of AEP; however, AEP can reduce more when the efficiency of collected landfill gas was increased as high as 90%. However, fertilizer will show the best scenario in AEP reduction when avoided product was included in the analysis.

(6) Estimation Aquatic Ecotoxicity (AE) and Terrestrial Ecotoxicity (TE) of each scenario

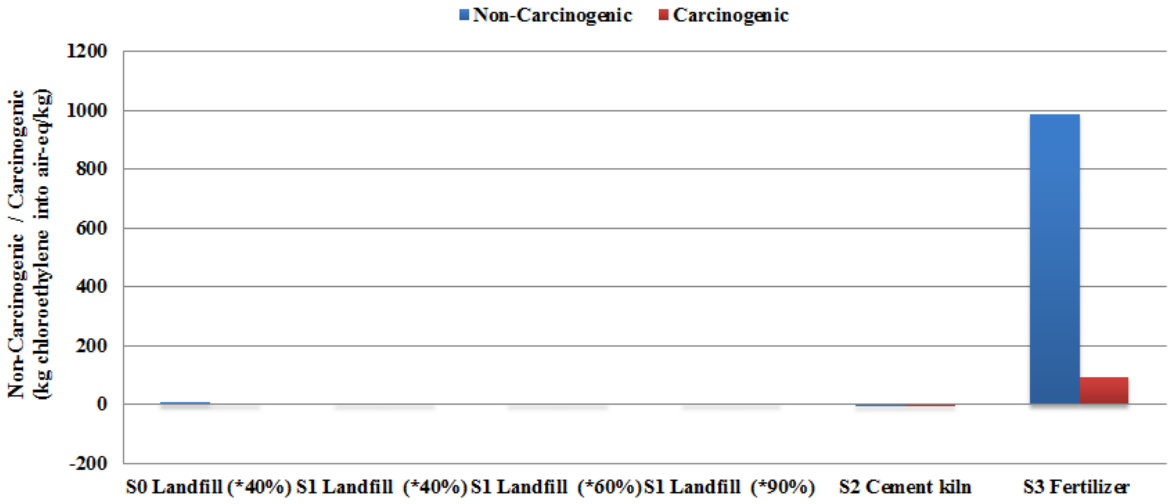


* refers to the efficiency of methane gas collection.

Figure 6.8 Aquatic Ecotoxicity (AE) and Terrestrial Ecotoxicity (TE) of each sludge scenario.

Aquatic Ecotoxicity (AE) and Terrestrial Ecotoxicity (TE) of each scenario are shown in Figure 6.8. AE is expressed as kg triethylene glycol-eq into water, while TE is expressed as kg triethylene glycol-eq into soil. Similar to the result of AEP, fertilizer option showed the greatest direct impact of AE and TE, followed by cement kiln option, and landfill option, respectively. In case of fertilizer option, heavy metal was a main pollutants contribution to soil which created great impact to ecotoxicity. For cement kiln option, the impact of ecotoxicity was generated from heavy metal emission to air. Nevertheless, the avoided product from replaced lignite coal showed significantly in AE reduction of scenario 2.

(7) Estimation Non-Carcinogenic Effects and Carcinogenic Effects of each scenario



* refers to the efficiency of methane gas collection.

Figure 6.9 Non-Carcinogenic Effects and Carcinogenic Effects of each sludge scenario.

Non-Carcinogenic Effects and Carcinogenic Effects of each scenario are shown in Figure 6.9. Among air pollutants that emitted from disposal options, ammonia gas (NH_3) and hydrogen sulfide (H_2S) were considered as the non-carcinogenic effects. Heavy metal that emitted to air and soil are also determined as the non-carcinogenic or carcinogenic effects depended on type of heavy metal. As shown in Figure 6.9, fertilizer option has shown highest impact of non-carcinogenic and carcinogenic effects, while landfill with 90% of collected landfill gas has shown the lowest impact of non-carcinogenic. Cement kiln has shown the best impact in term of carcinogenic effects. The H_2S treatment system does not reduce non-carcinogenic effects but it can reduce the effect of acidification instead. When landfill gas was combusted in gas engine, H_2S component in landfill gas will be converted to SO_2. That's mean high reduction in H_2S level, high reduction in acidification potential. However, the installation of H_2S removal unit not only reduce acidification potential but also reduce gas which has a characteristic odour of rotten eggs.

6.5.2 Copper slag

In this section, nine impact assessments of copper slag disposal in each option are shown in Figure 6.10 - Figure 6.13. The details are provided below.

(1) Estimation Global Warming Potential (GWP) of each scenario

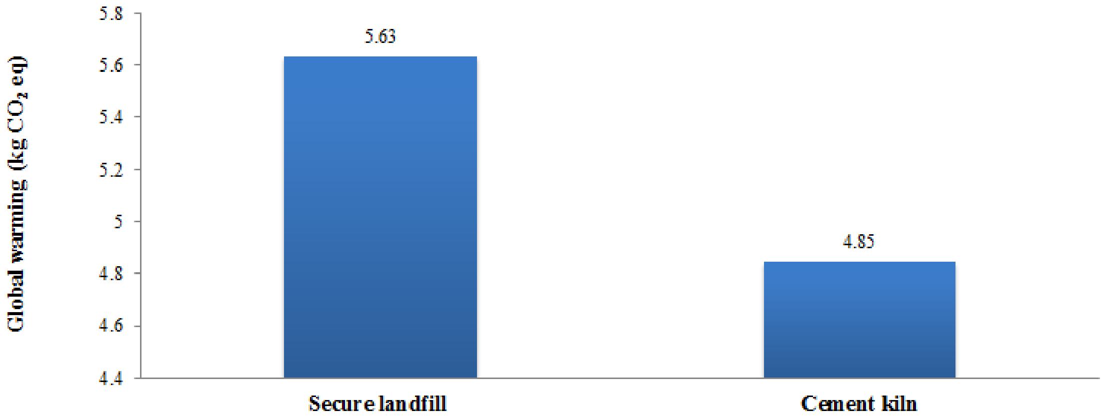


Figure 6.10 Global Warming Potential (GWP) of each copper slag scenario.

As shown in Figure 6.10, secure landfill option showed higher GWP than cement kiln option. The main source of GWP from both options is generated from the energy usage in operation. In case of cement kiln option, the direct emission of GWP from copper slag combustion is not generated because copper slag is an inorganic material. More than 50% of GWP from cement kiln option is generated in transportation section, while avoided clay material can reduce GWP only 0.2 kg CO_2-eq. In case of landfill option, main source of GWP is generated from fuel used for operation in the landfill site, and another source is generated from transportation section.

(2) Estimation Acidification Potential (AP) of each scenario

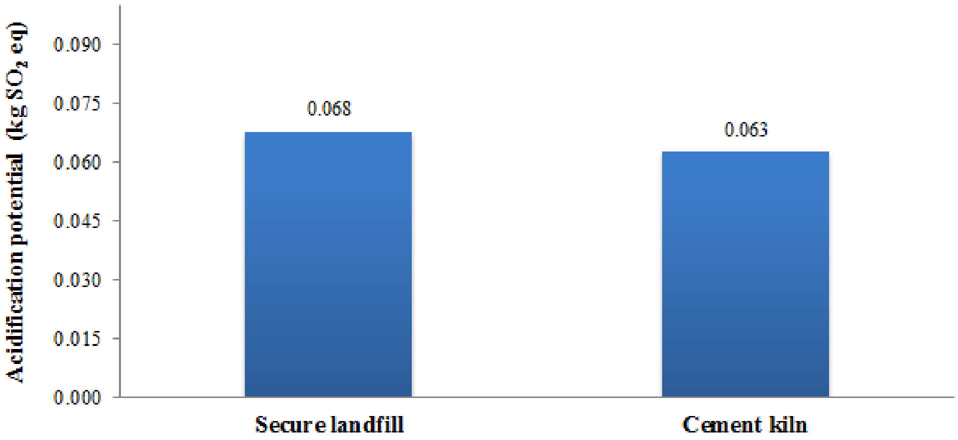


Figure 6.11 Acidification Potential (AP) of each copper slag scenario.

The calculation of AP in each scenario of copper slag disposal was shown in Figure 6.11. Obviously, the value of AP from both scenarios has close to similar value. More than 60% of AP generation from both scenarios are generated from transportation section.

(3) Estimation Respiratory Inorganic (RI) of each scenario

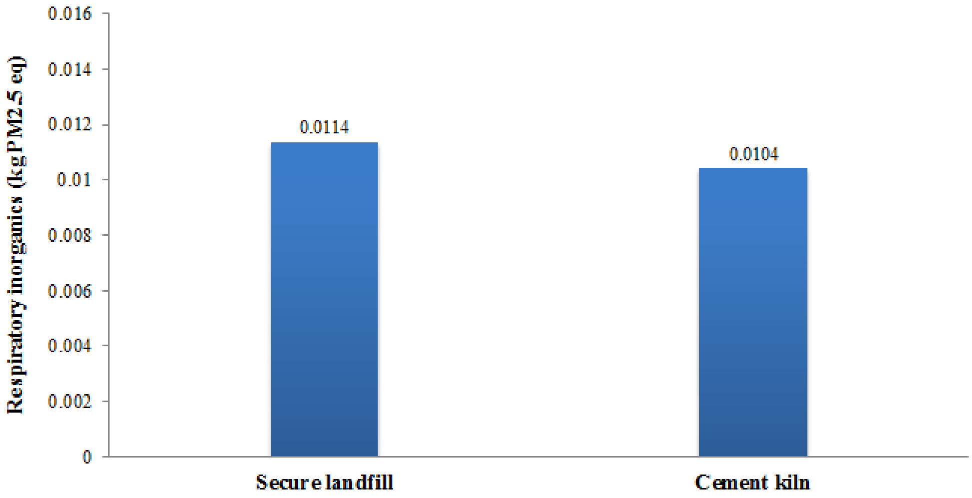


Figure 6.12 Respiratory Inorganic (RI) of each copper slag scenario.

Figure 6.12 shows the impact of respiratory inorganic from two disposal copper slag scenarios. In this impact category, both two scenarios have shown similar value of RI. More than 60% of RI from both scenarios are generated from the disposal process, while 40% of RI is generated from the transportation section.

(4) Estimation Non-Carcinogenic Effects and Carcinogenic Effects of each scenario

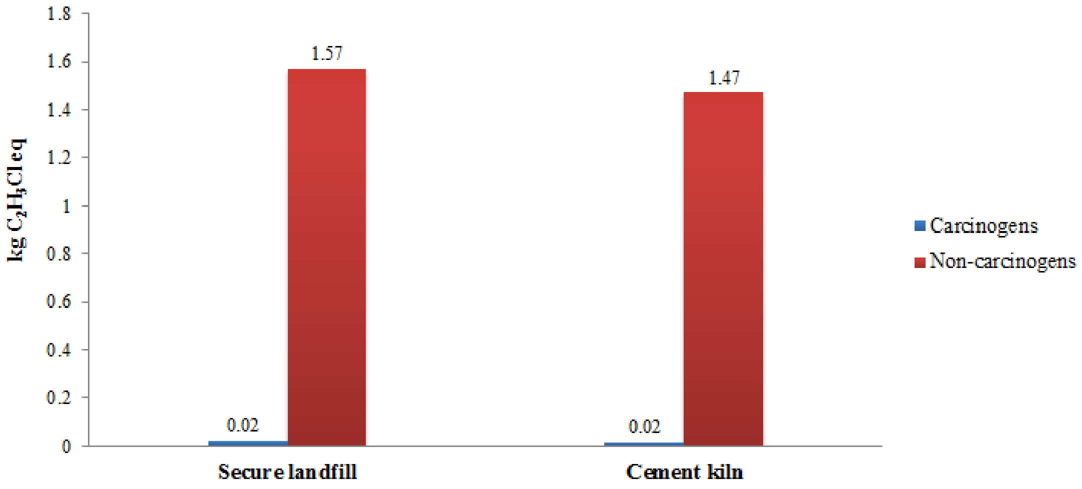


Figure 6.13 Non-Carcinogenic Effects and Carcinogenic Effects of each copper slag scenario.

Non-carcinogenic effect and Carcinogenic effect of each copper slag disposal scenario were shown in Figure 6.13. Both non-carcinogenic and carcinogenic effects, cement kiln option and landfill option showed the similar values of these impacts. In case of carcinogenic effect, the main source of this impact was generated from the disposal process (more than 60%). Conversely, in case of non-carcinogenic effect, the transportation section of both scenarios were the main source of this effect.

In addition, the other impacts of disposal copper slag, such as Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acid/nutri, and Aquatic eutrophication, are shown in Table 6.4. .

Table 6.4 The environmental impact of burn copper slag in cement kiln option compared with conventional option

Impact category	Secure landfill	Cement kiln	Unit
Aquatic ecotoxicity	14,116	9,806	kg TEG water
Terrestrial ecotoxicity	4.10	3.52	kg TEG soil
Terrestrial acid/nutri	0.3006	0.2761	kg SO2 eq
Aquatic eutrophication	0.0007	0.0004	kg PO4 P-lim

6.5.3 Refractory brick

In this section, nine impact assessments of refractory brick disposal in each option are shown in Figure 6.14 - Figure 6.17. The details are provided below.

(1) Estimation Global Warming Potential (GWP) of each scenario

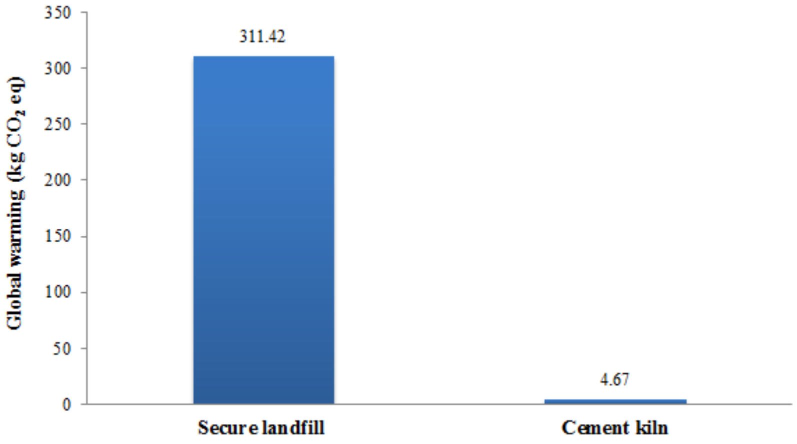


Figure 6.14 Global Warming Potential (GWP) of each refractory brick scenario.

The GWP from two scenarios of disposal refractory brick is shown in Figure 6.14. As can be seen, the GWP of landfill option is higher than cement kiln option. Although the composition of refractory brick is inorganic material as well as copper slag, the amount of GWP from landfill option is so different. This is because refractory brick must be stabilized before added to the landfill site in which this process consumes the cement product to operations. The main fraction of GWP from landfill option is generated from the production of cement.

(2) Estimation Acidification Potential (AP) of each scenario

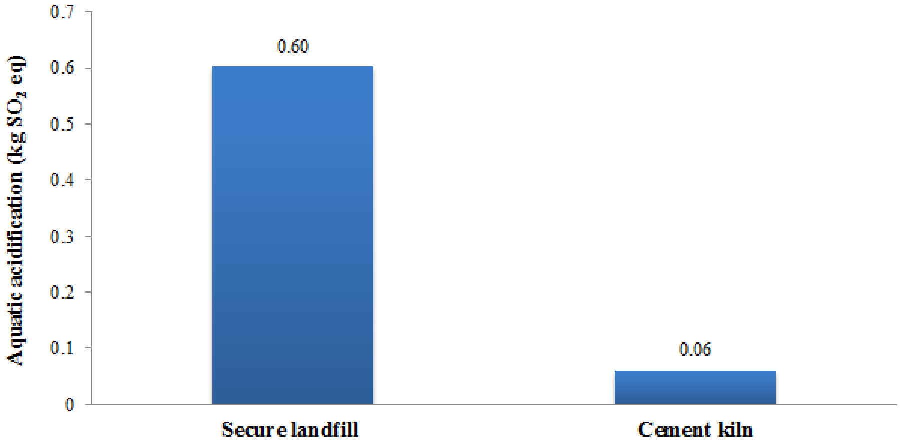


Figure 6.15 Acidification Potential (AP) of each refractory brick scenario.

In case of Acidification potential, the result of AP in each refractory brick scenario is shown in Figure 6.15. Obviously, the AP from landfill option is higher than cement kiln option, about 85% of AP from landfill option is generated from cement production.

(3) Estimation Respiratory Inorganic (RI) of each scenario

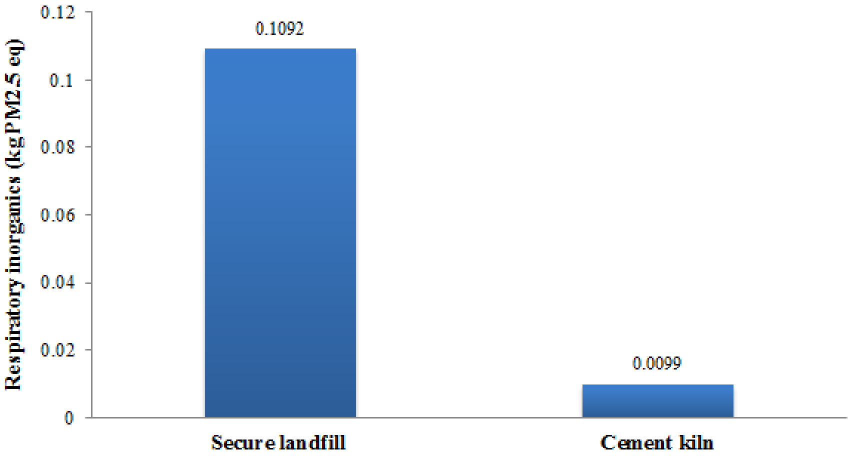


Figure 6.16 Respiratory Inorganic (RI) of each refractory brick scenario.

As can be seen in Figure 6.16, the trend of RI is the same as GWP. The main source of RI is generated from cement production process. The impact of RI from landfill option is 11 times compared to cement kiln option.

(4) Estimation Non-Carcinogenic Effects and Carcinogenic Effects of each scenario

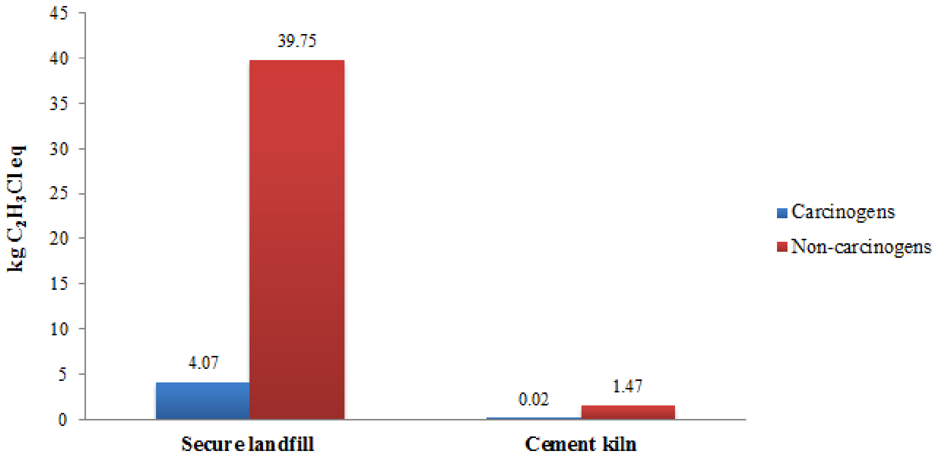


Figure 6.17 Non-Carcinogenic Effects and Carcinogenic Effects of each refractory brick scenario.

When determine the carcinogenic and non-carcinogenic effects, the result occurred the same trend as other impacts were shown. Landfill option showed highest impact in both carcinogenic and non-carcinogenic.

In addition, the other impacts of disposal refractory brick, such as Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acid/nutri, and Aquatic eutrophication, are shown in Table 6.5.

Table 6.5 Environmental impact of burn refractory brick in cement kiln option compared with conventional option

Impact category	Secure landfill	Cement kiln	Unit
Aquatic ecotoxicity	388,499	9,806	kg TEG water
Terrestrial ecotoxicity	941	3.32	kg TEG soil
Terrestrial acid/nutri	3.34	0.2636	kg SO2 eq
Aquatic eutrophication	0.0062	0.0004	kg PO4 P-lim

6.5.4 Contaminated container

In this section, nine impact assessments of contaminated container disposal in each option are shown in **Figure 6**.18 - **Figure 6**.21. The details are provided below.

(1) Estimation Global Warming Potential (GWP) of each scenario

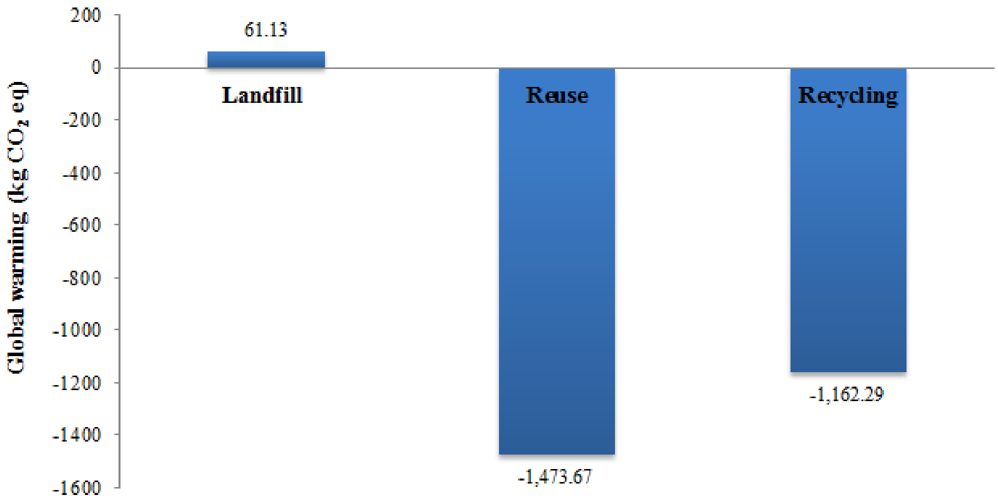


Figure 6.18 Global Warming Potential (GWP) of each contaminated container scenario.

Figure 6.18 reports the GWP from each scenario of contaminated container disposal. The result identified that reuse option has shown highest potential for reducing GWP (-1473.67 kg CO_2eq), followed by recycling option (-1.162.29 kg CO_2 eq). Meanwhile, landfill option emitted GWP to the environment, accounted for 61.13 kg CO_2eq. The main reduction of GWP from reuse option is coming from the avoided HDPE plastic product. Compared with recycling scenario, the main reduction of GWP is also generated from avoided HDPE plastic but the potential is less than reuse option. This is because the technology for recycling in this study can recycle HDPE plastic with the efficiency 88% of input raw material. From this situation, recycling option cannot replacing 100% of HDPE product; furthermore, it generates waste which need to disposal.

(2) Estimation Acidification Potential (AP) of each scenario

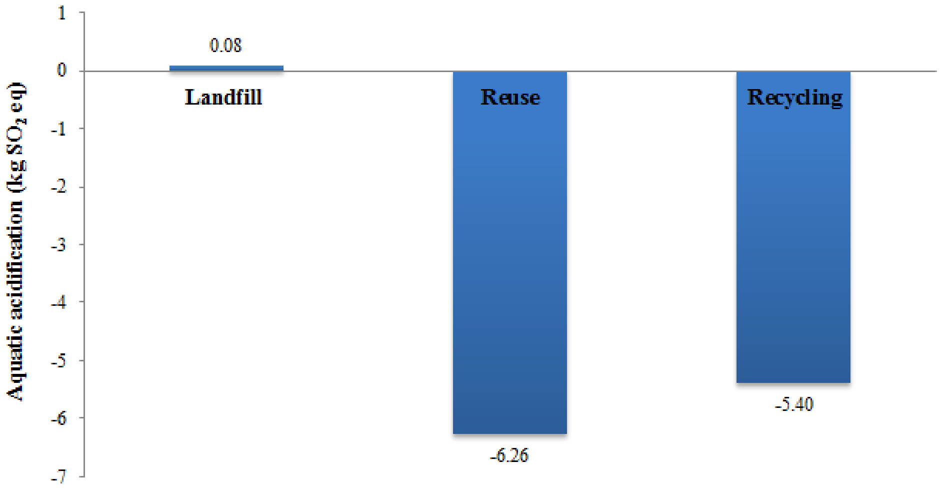


Figure 6.19 Acidification Potential (AP) of each contaminated container scenario.

Figure 6.19 reports the AP of each scenario of contaminated container disposal. As same as the result of GWP, reuse option still shows the highest potential for reducing AP (-6.26 kg SO_2eq), followed by recycling option (-5.40 kg SO_2eq). Avoided HDPE product is main AP reduction of both reuse and recycling options. In case of landfill option, AP is generated from fuel consumption for the operation.

(3) Estimation Respiratory Inorganic (RI) of each scenario

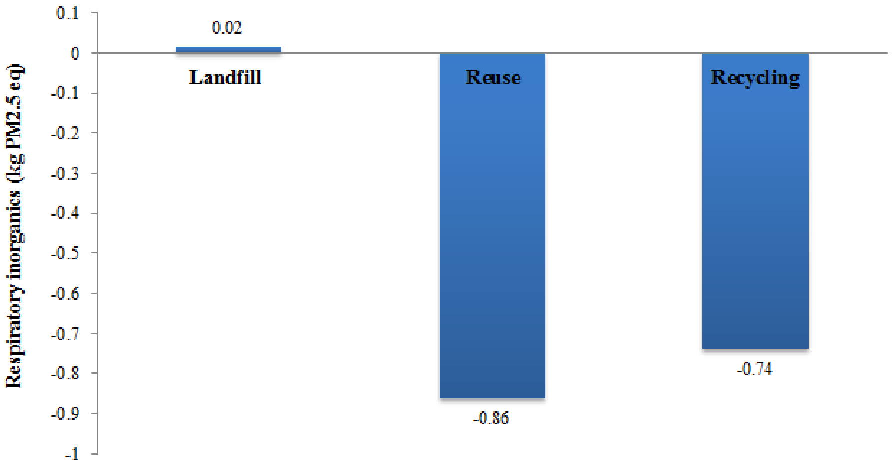


Figure 6.20 Respiratory Inorganic (RI) of each contaminated container scenario.

Figure 6.20 quantified the generation of RI of each scenario of contaminated container disposal. In this impact category, reuse option is the best option for reducing RI (-0.86 kg PM2.5 eq), followed by recycling option (-0.74 kg PM2.5 eq). Meanwhile, landfill option generates the RI impact to the environment, accounted for 0.02 kg PM2.5 eq.

(4) Estimation Non-Carcinogenic Effects and Carcinogenic Effects of each scenario

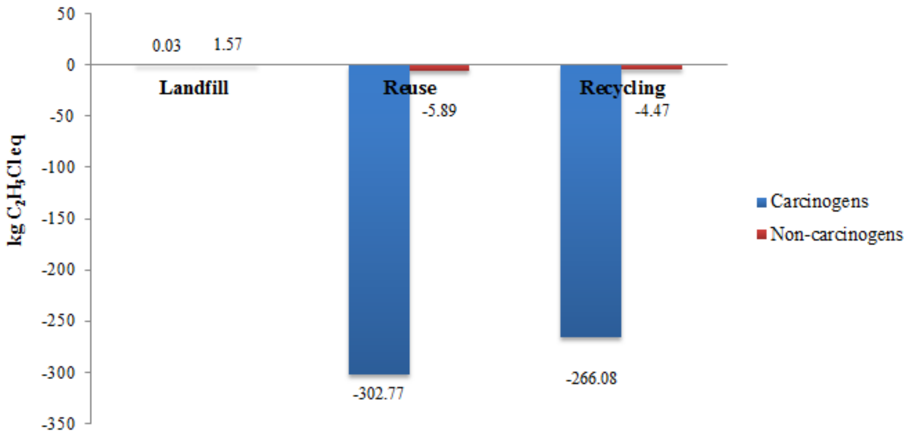


Figure 6.21 Non-Carcinogenic Effects and Carcinogenic Effects of each contaminated container scenario.

Figure 6.21 quantified the impact of carcinigenic and non-carcinogenic effects from each scenario of contaminated container disposal. The result shows that reuse and recycling options can reduce both carcinogenic and non-carcinogenic effects. Meanwhile, landfill option shows the generation of these impacts in small numbers.

The other impacts of disposal contaminated container, such as Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acid/nutri, and Aquatic eutrophication, are shown in Table 6.6.

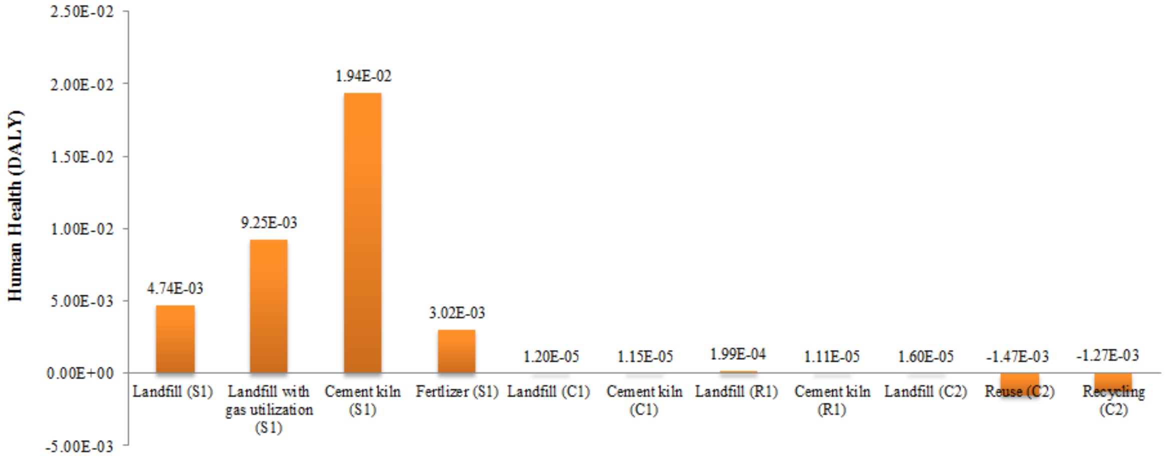
Table 6.6 Environmental impact of alternative options of contaminated container compared with conventional option

Impact category	Landfill	Reuse	Recycling	Unit
Aquatic ecotoxicity	10,144	-19,146	-12,156	kg TEG water
Terrestrial ecotoxicity	7.33	-45.5	-35.4	kg TEG soil
Terrestrial acid/nutri	0.4150	-20.7	-17.6	kg SO2 eq
Aquatic eutrophication	0.0040	-0.0075	-0.0055	kg PO4 P-lim

6.6 Damage categories

In this study, the result of mid-point characterization will be converted to three damage categories according to IMPACT 2002+ methodology, such as human health, ecosystem quality, and climate change. The details of each damage category are shown in the following section:

6.6.1 Human health

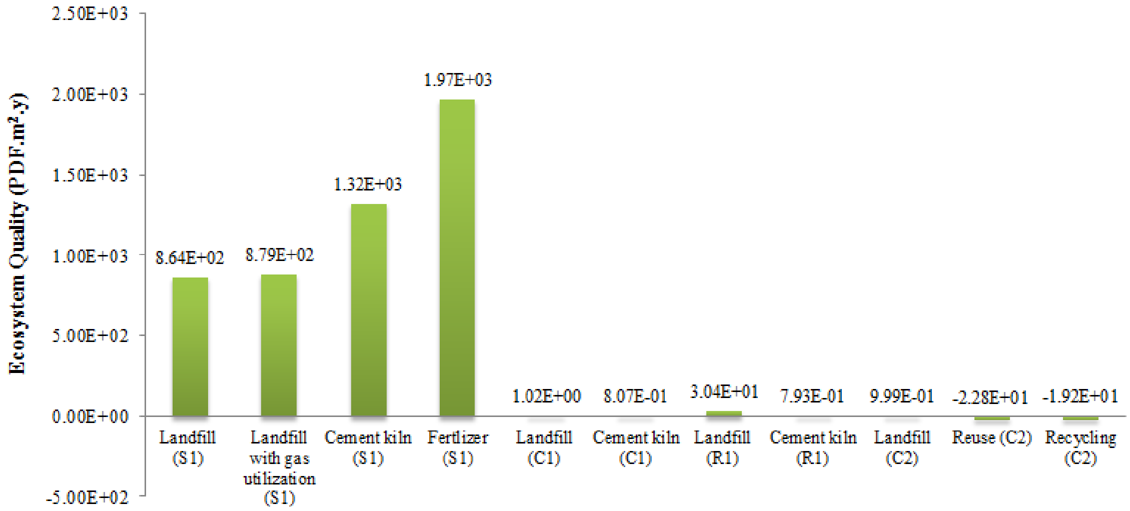


Note: (S) refers to sludge; (C1) refers to copper slag; (R1) refers to refractory brick; (C2) refers to contaminated container

Figure 6.22 Human health (DALY) damage in each scenario of petrochemical waste disposal

Figure 6.22 shows the Human health damage of each scenario. In case of sludge, the results demonstrate that fertilizer option shows the lowest damage in human health, while cement kiln option is highest. In case of copper slag and refractory brick, there are no significant differences in human health damage between landfill and cement kiln options. For contaminated container waste, reuse and recycling options show significant reduction in human health damage.

6.6.2 Ecosystem Quality

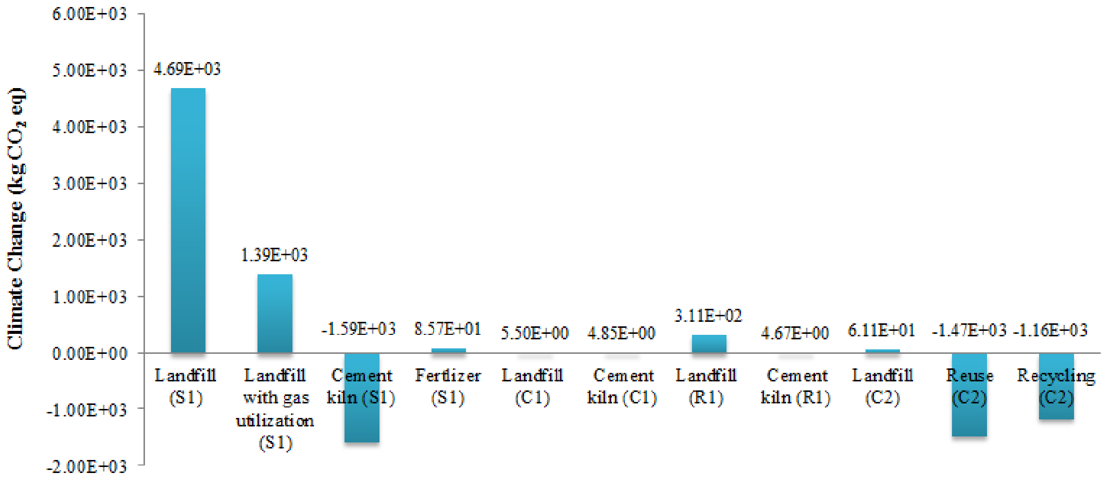


Note: (S) refers to sludge; (C1) refers to copper slag; (R1) refers to refractory brick; (C2) refers to contaminated container

Figure 6.23 Ecosystem quality (PDF.m^2.y) damage in each scenario of petrochemical waste disposal

When determine the ecosystem quality, fertilizer option has shown the highest impact, followed by cement kiln, landfill with gas utilization, and landfill option (as shown in Figure 6.23). For the other wastes, there are no significant for ecosystem quality damage generation.

6.6.3 Climate Change



Note: (S) refers to sludge; (C1) refers to copper slag; (R1) refers to refractory brick; (C2) refers to contaminated container

Figure 6.24 Climate change (kg CO_2eq) impact in each scenario of petrochemical waste disposal

As shown in Figure 6.24, in case of sludge, landfill with gas utilization has shown the significant potential to reduce climate change when compared with conventional landfill option. However, cement kiln has shown as the best option for reducing climate change. For contaminated container, reuse and recycling options have significant reduction in climate change.

6.7 Conclusion

This chapter analysed the alternative options for disposal petrochemical wastes in Thailand. The result was characterized into nine category impacts and then converted into the damage categories by using IMPACT 2002+ methodology. A sensitivity analysis was also conducted in this study to determine the particular variable in each scenario. The suitable option in each waste type can be concluded as follows:

Sludge from wastewater treatment system

In case of sludge, results demonstrate that landfill option (without electricity production) has proven to be worst case in term of climate change impact. Methane and carbon dioxide gases were generated in a large quantity by that option. To reduce the climate change impact, the collection of methane gas to produce electricity is very necessary. With 90% of methane collection efficiency, the emission of global warming potential could reduce approximately 32 times compared with conventional landfill option. In addition, it could be recommended that landfill gas should be treated H_2S before combusted in gas engine generator to reduce acidification potential. When determine the cement kiln option, the result indicates that its impact dominate on AP, RI, and TAN. To reduce AP, the increasing of SO_2 removal efficiency is an important factor. Although the SO_2 removal reaction could generate CO_2 emission, the quantity of CO_2 emission was proven with no significant in increasing of GWP.

The interesting point of cement kiln option is the impact of RI and TAN. As climate change is a hot issue to mitigation in Thailand, the recently schematic of improving waste management encourage the manufacturer to send industrial waste burning in cement kiln instead of landfill; without determination of other impacts. Burning is often generating large quantity of NO_2 which is the main cause of RI effect and it could lead to highest impact of human health as shown in the damage category.

In case of fertilizer option, it shows the highest impact of ecosystem quality in the section of damage category. The main impact contributed to ecosystem quality is generated from AE, TE, and AEP, in which heavy metal content of fertilizer production has emitted to soil. However, fertilizer option has shown high performance of the damage category in term of human health and climate change.

To conclude the result of suitable sludge disposal option, we suggest that fertilizer option should be selected as a first priority for disposal. However, it should be noted that the process of co-composting bio-sludge to produce fertilizer must have the standard and the heavy content in fertilizer product must have the concentration value according to the regulation of fertilizer production. In addition, we encourage that the fertilizer product that produce from bio-sludge should apply with flower-plant or garden tree to avoid the possibility of heavy metal ingestion to human. Second option should be landfill with gas utilization. The result is absolutely shown that its environmental performance is better than cement kiln.

Copper slag

As shown in the result of mid-point characterization and damage category, the impacts from landfill and cement kiln options are not different. However, we suggest that copper slag should be disposed of by cement kiln option as first priority. Although there are no significant differences for nine environmental impacts between two options, burning copper slag as co-material in cement kiln can lead to reduce natural resource consumption which create the benefit to the environment.

Refractory brick

The suitable option for disposal refractory brick should be cement kiln option. It is obviously that cement kiln option can reduce the environmental impact compared with conventional landfill option. Using cement material to stabilize waste before added to landfill site is main cause for generating environmental impact. On the other hand, burning refractory brick as co-material in cement kiln can lead to reduce GHG emission and other impacts.

Contaminated container

In case of contaminated container, it can be concluded that reuse is the best option to apply for this type of waste. With the reduction of 1,474 kg CO_2eq, reuse should be the first option for selected. The second option should be recycling option, this option can provide GHG reduction compared with landfill option. However, recycling option should be applied in case of reuse option is not feasible.

As shown in the previous section, LCA is necessary to analyse the life cycle of each waste. The environmental impact is depended on the characteristic of waste. It can be concluded that burn waste in cement kiln is not always suitable. Each option has an advantage and disadvantage points to determine. To help decision making for selecting the option, however, the indicator that based on the data of LCA should be created, and can compare the performance of selected 3R option. The detail of this indicator can be illustrated in the next chapter.

CHAPTER VII

EVALUATING THE PERFORMANCE OF 3R OPTIONS BY 3R INDICATOR (3RI): CASE STUDY OF POLYETHYLENE FACTORY IN THAILAND

After we pass chapter VI to VI, the results of 3R concept applied with petrochemical case study plants were shown that the 3R concept can reduce the amount of landfill wastes; it can also reduce cost of waste disposal and greenhouse gas emission. LCA was used as a tool to determine the environmental impact from waste management option in Chapter VI. Although the 3R project has good result from the petrochemical case study plants, the evaluating performance of the 3R project by using only percentage of landfill waste reduction has still ambiguous and not reflect to the 3R concept. In this chapter, therefore, the index that used to measure the capability of reducing waste simultaneously with reflection on the priority of 3R option is created. In this chapter, two polyethylene plants were selected as a case study. The implementation of 3R option will still be based on the existing survey results on landfill waste generated in polyethylene plants. After 3R options were applied to these plants, the 3R Indicator (3RI) was used as an indicator to measure the effectiveness of 3R project

7.1 3R Methodology

7.1.1 Identifying source of waste generation in polyethylene factory

At case study plants, the waste storage facility and waste treatment system were surveyed. The type of data obtained at this step included the sources of waste, types of waste, amounts of waste, and existing waste management options. After the survey was accomplished, the person responsible for waste management at the case study plants and the research team conducted a meeting to analyse the collected data. It should be noted that only landfill waste type was interested to propose 3R options.

7.2.2 Proposing and monitoring the 3R options

In this step, the data obtained in the first step were used as guidelines to propose 3R options. The options those suitable to apply with the factory were selected by environmental engineer, researcher, and waste manager. Then, action plans were created to implement the 3R options. After the proposed 3R options were selected, each one was monitored for a period of 12 months. The results were summarized and compared.

7.2.3 Evaluating the performance of 3R option

The performance of 3R options were evaluated by two points of view: the performance of 3R options based on quantitative measurement; and the performance of 3R options based on both quantitative and qualitative measurements. First indicator, the percentage of landfill waste reduction, the calculation is expressed by the following equation (Eq. 7.1).

$$\%Landfill\ waste\ reduction = \frac{(LF_{initial} - LF_{final})}{LF_{initial}} \times 100 \quad (7.1)$$

where, $LF_{initial}$ and LF_{final} are the amount of landfill waste before applied with 3R option and the amount of landfill waste after applied with 3R option, respectively.

In case of 3R indicator (3RI), which based on quantitative and qualitative measurements, was developed to evaluate the effectiveness in each of selected 3R option. Generally, the definition of indicators has been defined by various aspects; however, 3RI was defined as the value that can measure progress toward goal and objective of the project (EPA, 1996). To evaluate the performance of 3R project, 3RI was calculated according to Eq. 7.2 – Eq. 7.3.

$$LFR_{i,j} = \frac{LF_{initial} - LF_{final}}{LFG} \quad (7.2)$$

where, $LFR_{i,j}$ is the amount of landfill waste reduction; i is the type of landfill waste; j is the categories of 3R option (Reduce, Reuse, or Recycle); LFG is the total amount of landfill waste generated in 1 year. $LFR_{i,j}$ can gain extremely two values, 1 when LF_{final} is equal to zero that means the factory can reduce all landfill waste types, and 0 when $LF_{initial}$ is equal to LF_{final} that mean the factory cannot reduce any landfill waste at all. From Eq. 7.2, $LFR_{i,j}$ as dimensionless value was used to multiply with the weighting factor to convert the result as scores. The calculation was shown in Eq. 7.3.

$$3RI = \sum_{i=1}^{r} \sum_{j=1}^{3} \left(LFR_{i,j} \times \left(RP_j + EP_j + ENV_j \right) \right) \qquad (7.3)$$

where, 3RI is 3R indicator; RP_j is the score of 3R potential reduction of j option; EP_j is the score of economic impact of j option; and ENV_j is the score of environmental impact of j option.

According to the priority of 3R option, the reduce option was given the highest score, followed by reuse option, and recycling option, respectively (see in Figure 7.1). In addition, the economic impact was also determined in this study. The positive sign of economic impact (+3) refers to the option that gave revenue to the company. The negative sign of economic impact (0) refers to the option that factories must have additional payment for operations.

In case of environmental impact, it was divided into three subsections such as: life cycle assessment (LCA); Greenhouse gas (GHG) reduction; and Hazardous waste (HZW) reduction. Scores of the environmental impact in each subsection were shown in Figure 7.1. For LCA subsection, nine impact categories were determined in this study such as; the impact of Global Warming Potential (GWP), Acidification Potential (AP), Respiratory Inorganic (RI), Terrestrial Acidification and Nitrification (TAN), Aquatic Eutrophication Potential (AEP), Aquatic Ecotoxicity (AE), Terrestrial Ecotoxicity (TE), Non-Carcinogenic Effects, and Carcinogenic Effects. In each impact category, score 0.11 means the option shows lower impact than landfill option and score 0 means the option shows higher impact than landfill option. In case of GHG or HZW, score 1 means the option can reduce GHG emission or hazardous waste generation.

At the same amount of landfill waste reduction, high score of 3RI implies that the factory has high performance of operated 3R project.

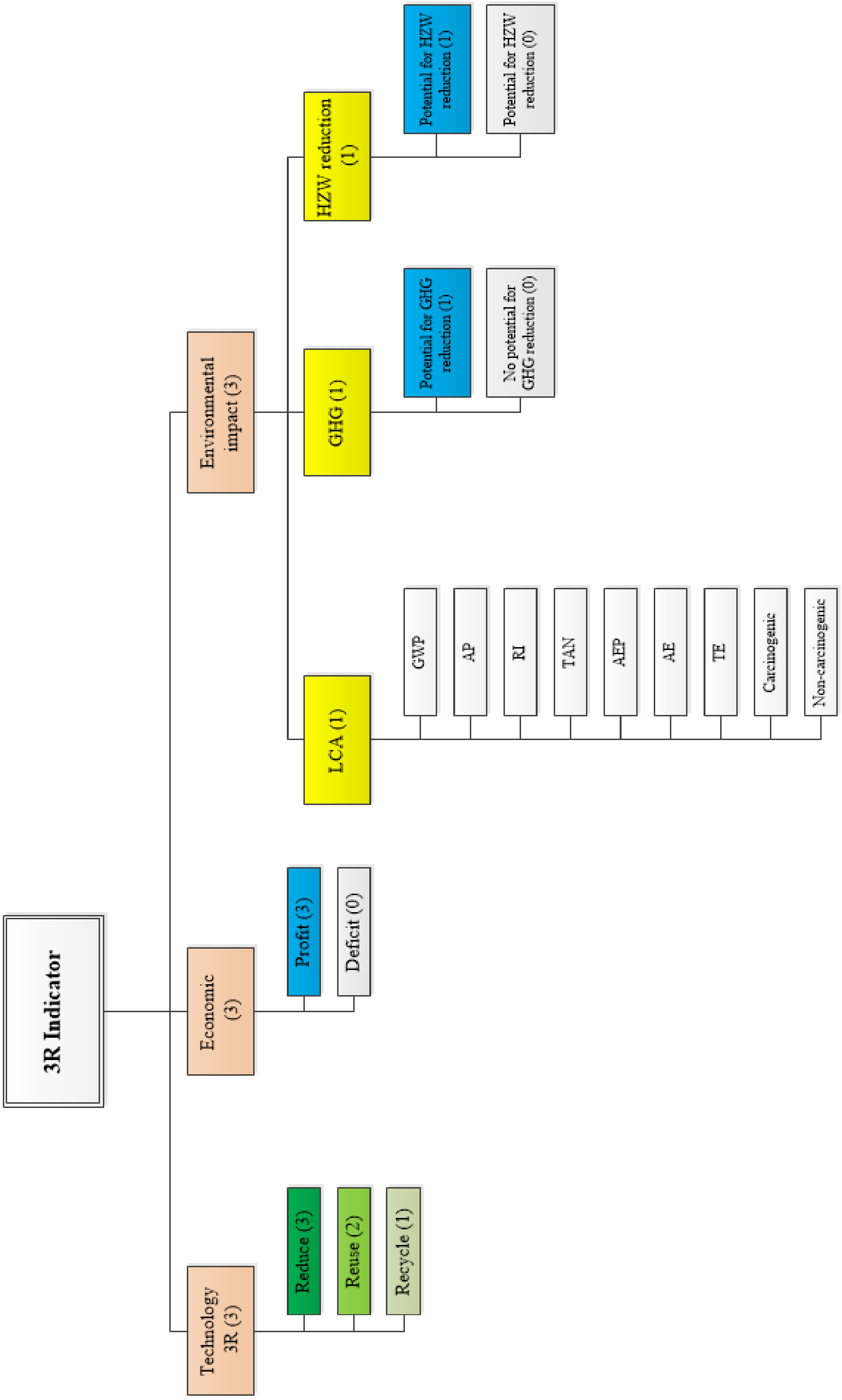


Figure 7.1 Weighting factor for 3R Indicator

7.2 Case study

In this study, two polyethylene plants were selected and surveyed as case studies for enhancing waste management system. Each plant produces different type of polyethylene products. The first plant produce only high density polyethylene (HDPE) product. Second factory consisted of two production lines such as low density polyethylene (LDPE) and linear low density polyethylene (LLDPE). The production capacity of HDPE, LDPE, and LLDPE are 300,000, 300,000, and 400,000 tons, respectively. All case-study plants are located in the Map Ta Phut Industrial Estate (MTPIE), Rayong province, in eastern Thailand.

7.3 Results and discussion

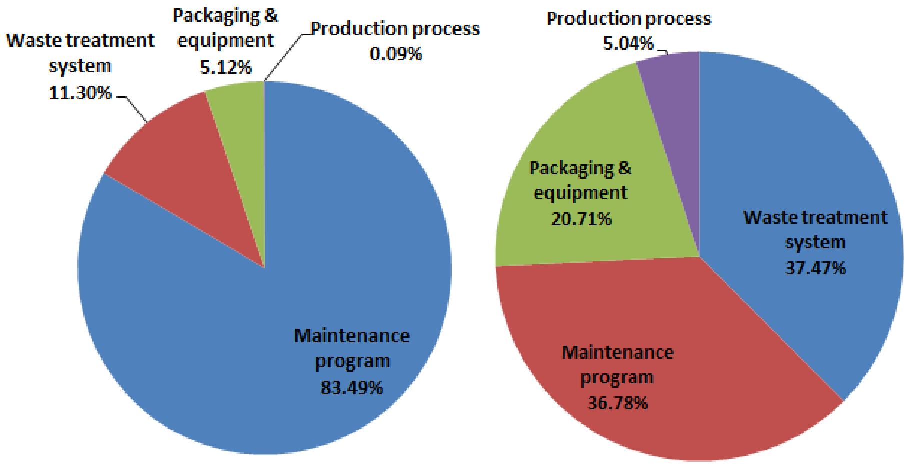
7.3.1 Waste sources and waste generation

As shown in Table 7.1, the list of industrial waste generated by the case study plants was identified. A total of 18 different types of industrial waste were generated from the different activities of the factory, such as the production process, the maintenance program, packaging and equipment, and waste treatment system. Some of industrial wastes (e.g. iron scrap, paper scrap, wood debris, plastic scrap, and aluminum scrap) were classified to be non-hazardous, while the remaining types were classified to be hazardous wastes. The fraction of hazardous waste was considered as 96% of total waste generated by the case study plants.

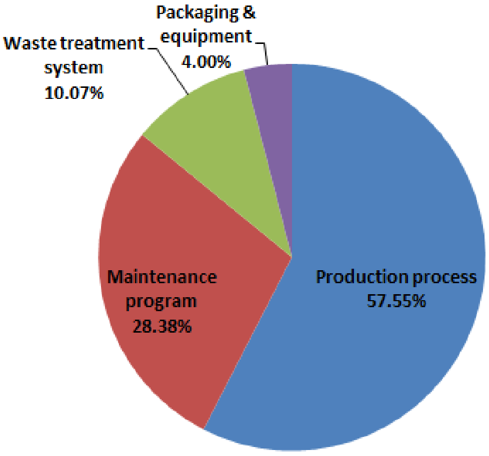
Table 7.1 List of identified industrial wastes in the case study plants

No.	Identified waste item	Waste types	LDPE	LLDPE	HDPE	Waste categories
1	Catalyst in mineral oil	Hazardous waste	×	×	-	Production process
2	Chemical cleaning water	Hazardous waste	×	×	×	Maintenance program
3	Contaminated container	Hazardous waste	×	×	-	Packaging & Equipment
4	Insulation	Hazardous waste	×	×	×	Packaging & Equipment
5	Lube oil	Hazardous waste	×	×	-	Maintenance program
6	Oil contaminated material	Hazardous waste	×	×	×	Packaging & Equipment

No.	Identified waste item	Waste types	LDPE	LLDPE	HDPE	Waste categories
7	Oil contaminated water	Hazardous waste	×	×	-	Maintenance program
8	Wastewater	Hazardous waste	×	×	-	Waste treatment system
9	Iron scrap	Non-hazardous	×	×	-	Packaging & Equipment
10	Paper scrap	Non-hazardous	×	×	-	Packaging & Equipment
11	Wood debris	Non-hazardous	×	×	-	Packaging & Equipment
12	Plastic scrap	Non-hazardous	×	×	-	Packaging & Equipment
13	Aluminum scrap	Non-hazardous	×	×	-	Packaging & Equipment
14	Oily sludge	Hazardous waste	-	-	×	Waste treatment system
15	Oligomer	Hazardous waste	-	-	×	Production process
16	Solid waste powder	Hazardous waste	-	-	×	Production process
17	Used oil	Hazardous waste	-	-	×	Maintenance program
18	Stabilizer bag	Hazardous waste	-	-	×	Packaging & Equipment



(a) LDPE plant (b) LLDPE plant



(c) HDPE plant

Figure 7.2 Waste generation based on factory activities

Four main sources of waste generation were identified based on the survey of the case study plants (as shown in Figure 7.2). From the survey, it was found that maintenance program and waste treatment system were the largest fraction of waste source in every case study plant. This may be because the case-study plants in that time were on shutdown plant and on meeting with the maintenance schedule. For the petrochemical factory, the timeframe of the survey is very sensitive to the type of waste generated. The amount of waste in each source can change over time depending on the activity of the plant in each year. For example, the largest fraction of waste source from HDPE plant in this study was production process (57.55%), followed by maintenance program (28.38%), waste treatment system (10.07%), and packaging and equipment (4.00%), respectively. Compared to the previous research, however, it was found that the main source of waste generation from HDPE plant was very different (Usapein and Chavalparit, 2013). This is one reason why the petrochemical factories are challenged to eliminate theirs industrial wastes. Therefore, we suggest that the strategy of 3R option is seen as the best way forward, particularly, applies to the petrochemical plant where large quantities of hazardous wastes are produced which the disposal seems extremely formidable.

7.3.2 Existing waste management option

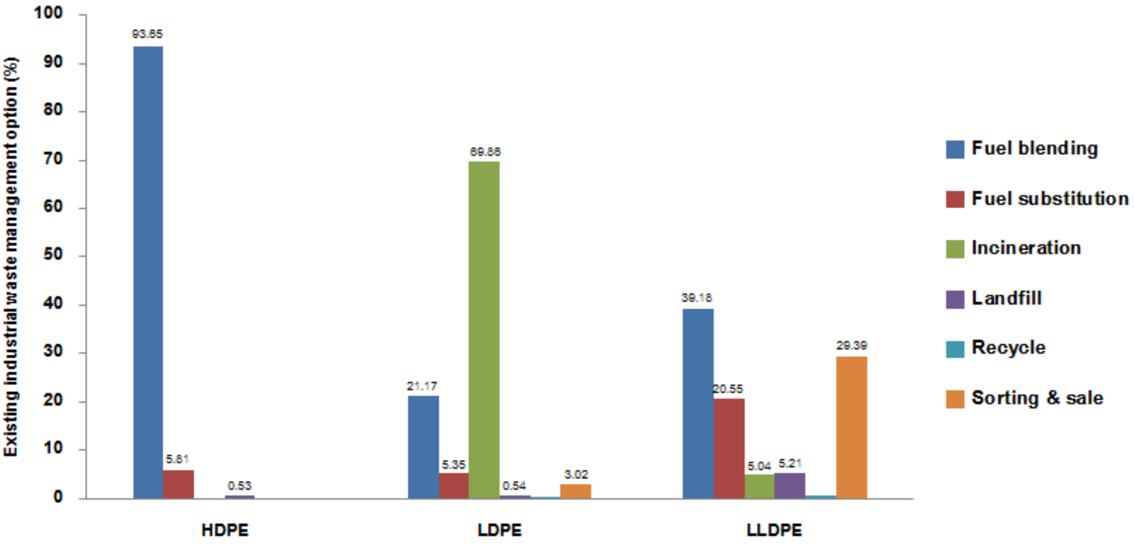


Figure 7.3 Existing waste management option in the case study plants (waste data from 2011)

With respect to existing waste management options, fuel substitution and fuel blending were substantial waste management options of the case-study plants, approximately 92.50% of total waste generated were disposed of by these options (see in Figure 7.3). Nevertheless, landfill option is still part of their waste management system (approximately 6.43% of total waste generated). This will be an important part in determining the degree of improvement that can be accomplished through the 3R concept. Therefore, the types of landfill waste were identified, such as insulation waste, contaminated container, and stabilizer bag. We found that all types of landfill wastes from the case study plants were considered as hazardous wastes which were disposed of by secure landfill.

7.3.3 Proposed 3R option

The proposed 3R option for reducing landfill wastes has been done by the previous research (Usapein and Chavalparit, 2013). In this study, however, the selected 3R option for the case study plants can be concluded as shown in Table 7.2. Before the 3R options were implemented, the total landfill waste listed in Table

7.2 (approximately 62 tons) will be disposed of by landfill option which resulted in a loss of natural resources and usable land. Nevertheless, after the 3R options were proposed and implemented, some petrochemical wastes were reused and recycled either as raw materials or as alternative energy sources for other factories. The reduction of landfill waste not only shows the benefit in term of environment but also creates a vision of corporate social responsibility, as a built-in and a self-regulating mechanism, to the public.

Table 7.2 Selected 3R options applied with the case study plants

Factory	Selected option	Waste reduction (tons)
LDPE	Reuse and recycle contaminated container	16.20
	Reuse insulation waste	3.00
LLDPE	Reuse and recycle contaminated container	12.00
	Reuse insulation waste	2.50
HDPE	Burn stabilizer bag as an alternative energy in a cement kiln	26.24
	Recycle contaminated container	1.83
	Total	61.77

7.3.4 Evaluation of the selected 3R options

After the 3R options were selected, the amount of landfill wastes were reduced. Figure 7.4 shows the result of implemented 3R options in a period of 12 months. HDPE plant shows the highest percentage of landfill wastes reduction (90.37%), followed by LLDPE plant (83.91%), and LDPE plant (79.50%). When we determine the effectiveness of operated 3R project by using the percentage of landfill waste reduction as an indicator, HDPE plant is a first rank by this point of view. However, this indicator can identify only the amount of landfill waste those reduced in each year, but it cannot clearly imply that the selected option is according to the principle of 3R concept.

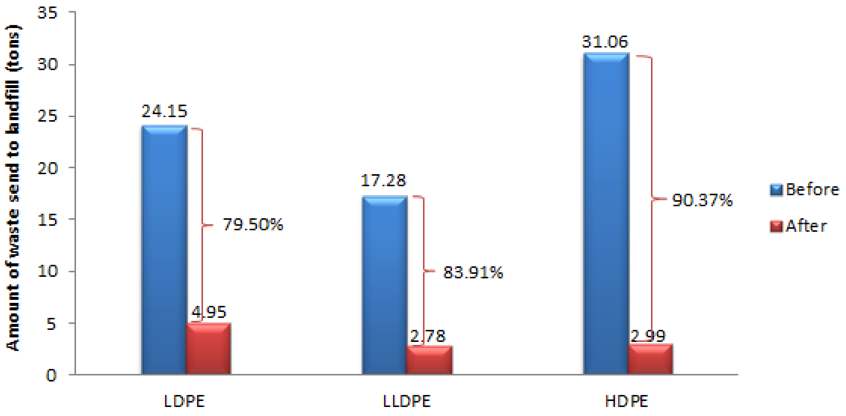


Figure 7.4 Annual landfill waste generated by the case study plants (waste data from 2012)

In this study, we propose the 3R Indicator (3RI) as a new indicator for evaluating the performance of operated 3R project. The result of score in each option can be shown in **Table 7.3**. Obviously, the reuse option will give high score than recycling option.

When evaluate the performance of 3R project by using 3RI, it was found that LLDPE plant has highest point of 3RI (4.39), followed by LDPE (4.36), and HDPE (3.42), respectively. Compared with the result in Figure 7.4, it could be seen that HDPE plant showed the highest percentage of landfill waste reduction but lowest in term of 3RI as shown in Figure 7.5.

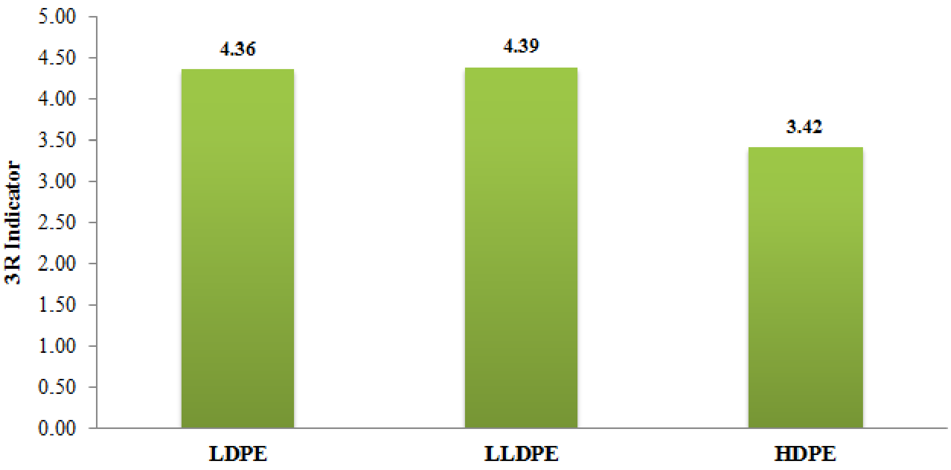


Figure 7.5 The evaluation of 3R project by using 3R Indicator (3RI)

Table 7.3 Score of 3RI in each selected 3R option

Table 7.3 Score of 3RI in each selected 3R option

Options	Technology (3)			Economic (3)		Environmental impact (3)		
	Reduce (3)	Reuse (2)	Recycle (1)	Profit (3)	Deficit (0)	LCA (1)	GHG (1)	HZW (1)
Reuse contaminated container	-	2	-	3	-	1.0	1	1
Reuse insulation waste	-	2	-	3	-	1.0	1	1
Recycling contaminated container	-	-	1	-	0	1.0	1	1
Burning stabilizer bag in cement kiln	-	-	1	-	0	0.8	1	1

This is because all options that applied with HDPE plant is recycling option which gave lower score than reuse option; furthermore, the economic impact of recycling option has shown negative sign for the company which resulted in the score even lower. LPDE and LLDPE have high score of 3RI because landfill wastes were mainly decreased by reuse options. From this view, if the factories want to get high score of 3RI, they should emphasize on the reduction and reuse options to apply with their plant at first.

7.4 Conclusion

Based on the data obtained, four main sources of waste generation are identified, such as maintenance program, packaging & equipment, production process, and waste treatment system. Maintenance wastes are significantly increased when the factory is on shutdown and turnaround program. Most of industrial solid wastes are classified as hazardous wastes since they contain chemicals or heavy metals. Burning waste as alternative energy is a main existing waste management option. However, they also dispose of some waste types, such as insulation waste, contaminated container, and stabilizer bag, in landfills. 3R options were proposed to minimize and divert landfill wastes to the recycling stream. The result demonstrated that HDPE showed the highest potential for reducing landfill wastes (90.37%), followed by LLDPE (83.91%), and LDPE (79.50%), respectively. Conversely, the new index (3RI) indicated that HDPE has lowest score when compared with LDPE and LLDPE due to their landfill wastes were mainly decreased by reuse options. LLDPE with the highest 3RI score will be regarded as the best performance of operated 3R project. It can be concluded that 3RI not only determines the capability of landfill waste reduction but also emphasizes on the priority of 3R option which is the key point of this concept. However, we suggest that 3RI should be useful to apply as the performance indicator within individual program due to its characteristic could not describe complete material cycles.

CHAPTER VIII

CONCLUSIONS AND RECCOMMENDATION

With the results those obtained from the previous chapters, the conclusions are demonstrated with respect to the research hypothesis and the objectives of this thesis. In addition, this chapter also contains recommendations for future research

8.1 Conclusions

In this study, three hypotheses were formed to proof that 3R concept can improve industrial waste management system of Thai petrochemical complex and respond to the objective of this study.

Hypothesis 1: The strategy of 3Rs could be applied to petrochemical complex to achieve zero waste to landfills.

To prove this hypothesis, three olefin factories were selected as a case study to apply the strategy of 3R option. After the survey, it could be stated that the Thai petrochemical plants considered in this study exhibit a high level of industrial waste recycling. Nevertheless, some types of wastes, such as bio-sludge, sludge, insulation, copper slag, molecular sieves, and contaminated containers, were disposed of in landfills. The comprehensive 3R methodology was applied to divert landfill waste to the recycling stream. Various options were proposed to improve the waste management system. Three main options were selected, and the implementation of these options reduced the amount of landfill waste by approximately 79.01%.

In case of HDPE factory, the 3R practices, which prioritized the 3R’s (reduce, reuse, and recycle) in order to minimize waste generation and environmental impacts, were applied to the factory. The implementation of the selected 3R options over the course of one year was able to decrease wastes sent to landfill by 33.88% (w/w).

From the result, it can be concluded that 3R strategy could be applied to petrochemical complex for reducing the amount of landfill waste. Obviously, it has shown high potential of waste reduction for applying with petrochemical industry. In addition, 3R strategy can not only reduce waste at source but also divert waste from landfill to the recycling stream. With this success, it may be because 3R concept is easy for the people responsible for waste management at the factory to understand and imitate. Compared with other concepts, the highlight of 3R concept is the prioritized the 3R's (reduce, reuse, and recycle). The first awareness of the factory should try to start from reduction waste at source and reuse as much as possible. In spite of the last R (Recycling) will benefit the environment, it also emits the pollutant from the process to the environment.

At the ultimate target, it is very difficult to reduce landfill waste until zero because some waste types cannot recycle in Thailand due to lack of the technology to recycling. Although sorting process improved the industrial waste management system, the wastes that cannot be reused are still disposed of at landfills.

Hypothesis 2: The integrated industrial solid waste management scenario, combining different improvement 3Rs options, could achieve GHG mitigation potential.

After 3R options were selected to the case study plants, each selected option can show the amount of greenhouse gas reductions. From the result of olefin factory, the combining different 3Rs options could reduce 152.49 tons CO_2 eq.

In case of HDPE factory, when using waste as alternative fuel in cement kiln, both waste polymer and boxes/packaging show less greenhouse gas emission than bituminous coal. We conclude that diverted waste from landfill to burn as an alternative fuel is a good option for improving waste management system of HDPE plant.

It is certainly to state that the 3R option could reduce greenhouse gas emission compared with the landfill option as shown from the petrochemical case study plants.

Hypothesis 3: Petrochemical complex could develop solid waste management system for toward sustainable waste management.

The result from our implement 3R option indicates that 3R option could develop solid waste management for toward sustainable waste management. For example, the olefin plants could reduce their cost of waste disposal by 453,308 baht/year; meanwhile; they also reduce greenhouse gas emission by 152.49 tons CO_2 eq./year. With this situation, 3R option can lead to the sustainability of waste management in petrochemical complex.

From all above conclusions, this thesis demonstrates that 3R concept is an effective tool for improving industrial waste management system in petrochemical industry in which it can completely respond to the objective of this study. Therefore, it should be discussed and proposed to create the 3R strategy for using as a guideline for other factories.

8.2 Discussion: 3R strategy to improve industrial waste management system

With the data collection and 3R project experience from petrochemical case study plants, it can be concluded and proposed to the strategy of improving industrial waste management system toward to zero landfill wastes in which it expected to be used as a guideline for improving waste management system at the factory level.

A strategy to improve industrial solid waste management system of the Thai petrochemical complex through 3Rs concept is shown in Figure 8.1. The strategy can be divided into 3 phases as follows.

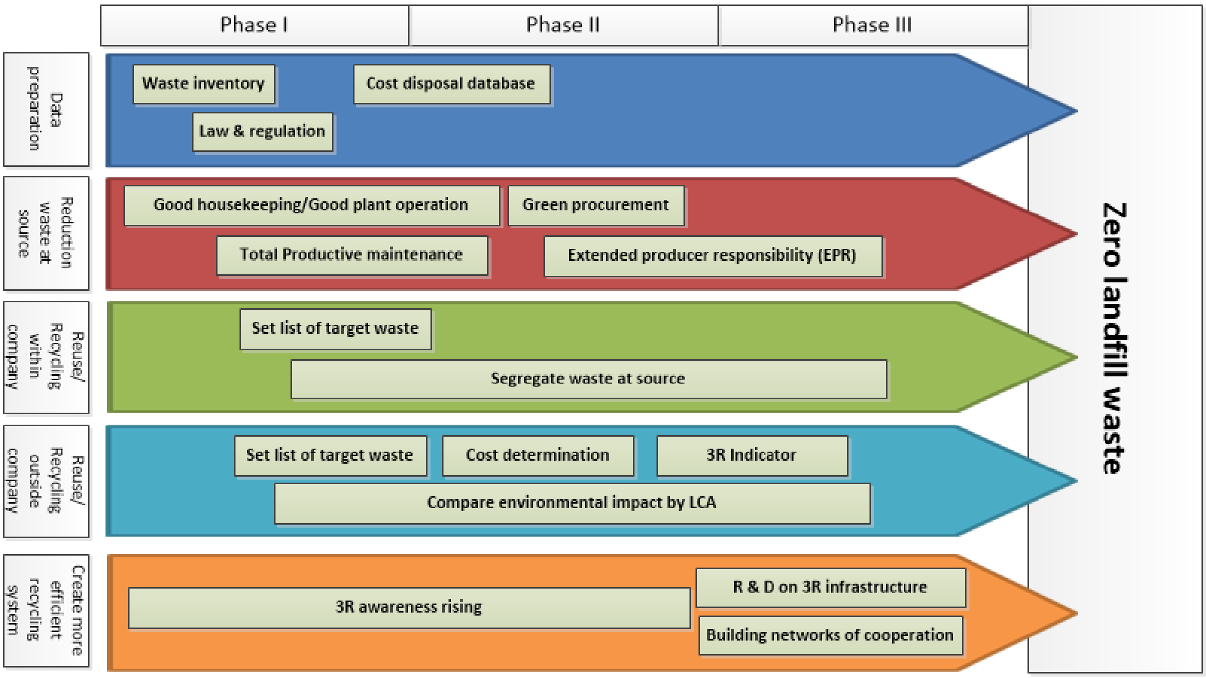


Figure 8.1 Strategy to improve industrial solid waste management in the factory

Phase I: create waste inventory and reduction waste at source. At the beginning of zero landfill waste strategy, waste inventory must be created to identify the status of waste management system of the factory. The expected results from waste inventory are the share percentage of landfill waste, type of waste that disposed of by landfill, and the quantity in each type of landfill waste. After waste inventory was created, the target list of landfill waste was set. Most of wastes generated from petrochemical factory were classified as hazardous waste; therefore, it should attend to isolate contaminated waste and non-contaminated waste from each other. With this concern, it can be resulted in reduction of hazardous waste. Reduction waste at source is also operated in this phase. The principal of good housekeeping and total preventive maintenance program should be introduced to the petrochemical factory. This object will help to increase the awareness of waste generation to the employee. However, the data on law and regulation of waste management should be concentrated to avoid the illegal practices, especially the option that applied for hazardous waste.

Phase II: The target of landfill waste was listed and option for reuse/recycling should be proposed. Mixing type of industrial waste should be segregated, for example, packaging waste, insulator waste, contaminated container, uncontaminated container, etc. When the option for reuse/recycling was proposed, it is necessary to check that the option is comply with the law and regulation of waste management for petrochemical factory. After reuse/recycling within company is not feasible, reuse/recycling outside company should be introduced. Typically, the alternative option outside company will be easier than the option within company. This may be because the petrochemical factory has high level of safety regulation due to its process involved with flammable materials. Sometime the selected option is not always friendly with the environment compared with existing option. Therefore, life cycle assessment should be applied as a tool for decision making. To evaluate the performance of the project, in addition, the indicator should be created. In this study, we suggest 3R indicator (3RI) for evaluating the performance of the project. To increase the effective of 3R methodology, it is necessary to suggest that green procurement and extended producer responsibility should be introduced to the factory for reducing waste generation at source. Green supply chain such as: green procurement and extended producer responsibility (EPR) should be established. This strategy could lead to increase the material that can be recycled by available technology.

Phase III: The last phase of this strategy is related with research development and technology. Petrochemical companies should encourage to research on waste utilization for building a cognitive basis and leading to the recycling waste at industrial scale. Cooperation with waste processor is also important to improve waste management system for petrochemical factory. In the context of this partnership, it means the understanding between waste generator (petrochemical factory) and waste processor. Sometime the waste characteristic is not matched with the requirement of waste processor. To increase the capacity of recycling waste, the collaborative research for waste utilization is recommended for leading to more recycling waste in the future. By the way, rising in 3R awareness still necessary and need to concern every time throughout the strategy.

8.3 Recommendations

The results from petrochemical case study showed that some landfill wastes still disposed by landfill method such as insulator wastes (rock wool, ceramic wool); therefore, it is urgently to research on the alternative option for utilization of these wastes. In addition, the disposal cost of recycling options is very high compared to landfill option. Therefore, it should be recommended that the Thai government should establish the scheme of landfill tax to encourage the manufacturer avoided disposal industrial waste by landfill option.

Future research could be attained to both waste utilization and waste management policy. These will lead to not only reducing waste generation but also creating sustainable waste management system in Thai petrochemical industry.

REFERENCES

Abduli, M., Abbasi, M., Nasrabadi, T., Hoveidi, H., and Razmkhah, N. Solid Waste Management in Tabriz Petrochemical Complex. Iran. J. Environ. Health. Sci. Eng. 3 (2006): 185-192.

Alshammari, J. S., Gad, F. K., A.M.E, A., and Khan, A. R. Solid Waste Management in Petroleum Refineries. Amer J Env Sci 4 (2008): 397-405.

Aranda-Usón, A., Ferreira, G., López-Sabirón, A. M., Sastresa, E. L., and de Guinoa, A. S. Characterisation and Environmental Analysis of Sewage Sludge as Secondary Fuel for Cement Manufacturing. Chemical Engineering Transactions 29 (2012).

Arworn, P., and Chavalparit, O. "Utilization of Bio-Sludge from Olefin Wastewater Treatment Plant as Co-Composting Material " The 9th Kasetsart University Conference. Kamphaengsaen Campus, Nakorn Pathom, Thailand: Kasertsart University 2012. 15-23.

Bhattacharjee, S. The Expert System for Thermodynamics 2014. Available: http://www.thermofluids.net/. March 6 2014.

Brokerage, R. A. "Thermal and Coking Coal, Standard Export, Specification ". Indonesia R & A Brokerage, LLC 2013.

Buyukkamaci, N., and Kucukselek, E. Improvement of Dewatering Capacity of a Petrochemical Sludge. J Hazard Mater 144,1-2 (2007): 323-327.

Cederberg, C. "Agricultural Consultant ". Halmstad, Sweden 2004.

Charles, A. T., and "Oil Mist Lubrication for the Petrochemical Industry." 11th International Pump Users Symposium. Texas: the Turbomachinery Laboratory, Department of Mechanical Engineering, A&M University Press, 1994.

Charmondusit, K., and Keartpakpraek, K. Eco-Efficiency Evaluation of the Petroleum and Petrochemical Group in the Map Ta Phut Industrial Estate, Thailand. Journal of Cleaner Production 19,2-3 (2011): 241-252.

Chavalparit, O., Rulkens, W. H., Mol, A. P. J., and Khaodhair, S. Options for Environmental Sustainability of the Crude Palm Oil Industry in Thailand through Enhancement of Industrial Ecosystems. Environment, Development and Sustainability 8,2 (2006): 271-287.

Chaya, W., and Gheewala, S. H. Life Cycle Assessment of Msw-to-Energy Schemes in Thailand. Journal of Cleaner Production 15,15 (2007): 1463-1468.

Chen, J., Jiang, L., and Sha, H. Removal Efficiency of High-Concentration H2s in a Pilot-Scale Biotrickling Filter. Environmental Technology 27,7 (2006): 759-766.

Cherubini, F., Bargigli, S., and Ulgiati, S. Life Cycle Assessment (Lca) of Waste Management Strategies: Landfilling, Sorting Plant and Incineration. Energy 34,12 (2009): 2116-2123.

Cleary, J. Life Cycle Assessments of Municipal Solid Waste Management Systems: A Comparative Analysis of Selected Peer-Reviewed Literature. Environ Int 35,8 (2009): 1256-1266.

CSD-18. Commission on Sustainable Development. New York, The United States: United Nations 2010.

Cuéllar, A. D., and Webber, M. E. Cow Power: The Energy and Emissions Benefits of Converting Manure to Biogas. Environmental Research Letters 3,3 (2008).

Damanhuri, E., Wahyu, I. M., Ramang, R., and Padmi, T. Evaluation of Municipal Solid Waste Flow in the Bandung Metropolitan Area, Indonesia. Journal of Material Cycles and Waste Management 11,3 (2009): 270-276.

De Haan, S., and Sullivan, B. K. Overview of Cracked Gas Compressor Fouling: Theories and Practices. 2001. Available: http://dc127.4shared.com/doc/1bO4XI1R/preview.html April 4 2012

DEDE. A Study on Energy Efficiency Index in Petrochemical Industry. Bangkok, Thailand Department of Alternative Energy Development and Efficiency, Ministry of Energy 2006.

Demirbas, A. Waste Management, Waste Resource Facilities and Waste Conversion Processes Energ Convers Manage 52 (2011): 1280–1287.

Dhuyvetter, I., Reyniers, M. F., Froment, G. F., and Marin, G. B. The Influence of Dimethyl Disulfide on Naphtha Steam Cracking. Ind Eng Chem Res 40 (2001): 4353-4362.

Diaz, L. F. "The 3rs as the Basis for Sustainable Waste Management: Moving Towards Zero Waste." Sustainable Production and Consumption/3R: United Nations Centre for Regional Development 2011.

DIWs. Guideline for Industrial Wastes Utilization: Final Report Bangkok Department of Industrial Works 2009.

DIWs. Guideline for Treating and Disposal Industrial Wastes: Department of Industrial Works 2011.

DIWs. The Waste Management Master Plan and Feasibility Study to Establish the Collection and Handling of Industrial Waste. Bangkok Department of Industrial Works, 2008.

Djedidi, Z., et al. Metals Removal from Soil, Fly Ash and Sewage Sludge Leachates by Precipitation and Dewatering Properties of the Generated Sludge. J Hazard Mater 172,2-3 (2009): 1372-1382.

Dong, L., et al. Environmental and Economic Gains of Industrial Symbiosis for Chinese Iron/Steel Industry: Kawasaki's Experience and Practice in Liuzhou and Jinan. Journal of Cleaner Production 59 (2013): 226-238.

ECA. Cement Manufacturing Process. 2013. European Cement Association. Available: http://www.cembureau.be/about-cement/cement-manufacturing-process.

EcoinventCentre. "Ecoinvent Data V2.0 Final Reports Ecoinvent 2000 No. 1-15. ." Swiss Centre for Life Cycle Inventories Ed. E. Centre. Dudendolf 2007.

EcoinventCentre. Ecoinvent Data V 2.1: Swiss Centre for Life Cycle Inventories 2009.

EPA. Air Pollution Control Fact Sheet United States: Environmental Protection Agency (EPA) 2003.

EPA. Environmental Indicators of Water Quality in the United States. United States of America: United States Environmental Protection Agency 1996.

Flodman, M. Emissions of Methane, Nitrous Oxide and Ammonia from Storing of Digested Sludge. Upsala, Sweden Sweden University of Agricultural Sciences, 2002.

Fore, S., and Mbohwa, C. T. Cleaner Production for Environmental Conscious Manufacturing in the Foundry Industry. Journal of Engineering, Design and Technology 8,3 (2010): 314-333.

Garner, A., and Keoleian, G. A. Industrial Ecology: An Introduction. The United States National Pollution Prevention Center for Higher Education, University of Michigan 1995.

Garverick, L. Corrosion in the Petrochemical Industry. Ohio: ASM International, Metals Park, 1994.

Gary, J. H., and Handwerk, G. E. Petroleum Refining Technology and Economics. 2nd ed: Marcel Dekker, Inc. , 1984.

Gibbs, D., and Deutz, P. Implementing Industrial Ecology? Planning for Eco-Industrial Parks in the USA. Geoforum 36,4 (2005): 452-464.

Goedkoop, M., and Spriensma, R. The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Assessment: Methodology Report. Netherlands: Pre Consultants, Amersfoort (NL), 2000.

GTZ-Holcim. Guidelines on Co-Processing Waste Materials in Cement Production. Offenbach, Germany GTZ-Holcim Public Private Partnership 2006.

Guinee, J. B., et al. Life Cycle Assessment: An Operational Guide to the Iso Standards. Kluwer Academic Publishers, Dordrecht (NL), 2002.

Hong, J., and Li, X. Environmental Assessment of Sewage Sludge as Secondary Raw Material in Cement Production--a Case Study in China. Waste Manag 31,6 (2011): 1364-1371.

Hong, J., Li, X., and Zhaojie, C. Life Cycle Assessment of Four Municipal Solid Waste Management Scenarios in China. Waste Manag 30,11 (2010): 2362-2369.

Hu, G., Li, J., and Zeng, G. Recent Development in the Treatment of Oily Sludge from Petroleum Industry: A Review. J Hazard Mater 261 (2013): 470-490.

Humbert, S., Schryver, A. D., Bengoa, X., Margni, M., and Jolliet, O. Impact 2002+: User Guide: Quantis Sustainability counts, 2012.

Husillos Rodríguez, N., et al. The Effect of Using Thermally Dried Sewage Sludge as an Alternative fuel on Portland Cement Clinker Production. Journal of Cleaner Production 52 (2013): 94-102.

IFC. Environmental, Health and Safety Guidelines for Large Volume Petroleum-Based Organic Chemicals Manufacturing: International Finance Corporation, World Bank Group, 2007.

IPPC. Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries: Integrated Pollution Prevention and Control, 2001.

Iraldo, F., Testa, F., and Bartolozzi, I. An Application of Life Cycle Assessment (Lca) as a Green Marketing Tool for Agricultural Products: The Case of Extra-Virgin Olive Oil in Val Di Cornia, Italy. Journal of Environmental Planning and Management 57,1 (2014): 78-103.

IWMB. Industrial Waste Management Bureau 2011 2011. Available: http://www2.diw.go.th/iwmb/2012.

Johansson, K., Perzon, M., Fröling, M., Mossakowska, A., and Svanström, M. Sewage Sludge Handling with Phosphorus Utilization – Life Cycle Assessment of Four Alternatives. Journal of Cleaner Production 16,1 (2008): 135-151.

Jolliet, O., et al. Impact 2002+: A New Life Cycle Impact Assessment Methodology. The International Journal of Life Cycle Assessment 8,6 (2003): 324-330.

JRC. Supporting Environmentally Sound Decisions for Waste Management. Italy: Institute for Environment and Sustainability, Joint Research Centre, European Commission, 2011.

Kaosa-ard, M., Laplante, B., Rayanakorn, K., and Waranyuwattana, S. Thailand: Capacity Building for Pollution Taxation and Resource Mobilization for Environmental and Natural Resources Sectors — Phase Ii. Thailand: Asian Development Bank, 2008.

Katherine, N. P., and Thomas, C. B. "The Evolution of Hazardous Waste Programs: Lessons from Eight Countries." Center for Risk Management Resources for the Future, 2012.

Kiatkittipong, W., Wongsuchoto, P., and Pavasant, P. Life Cycle Assessment of Bagasse Waste Management Options. Waste Manag 29,5 (2009): 1628-1633.

Kightley, D., Nedwell, D. B., and Cooper, M. Capacity for Methane Oxidation in Landfill Cover Soils Measured in Laboratory-Scale Soil Microcosms. Applied and Environmental Microbiology 61,2 (1995): 592-601.

Koch-glitsch. Intalox Packed Column. 2010. Available: http://www.koch-glitsch.com. Nov 10 2011.

Kohl, A., and Nielson, R. Gas Purification. 5th ed: Gulf Publishing, 1997.

Lederer, J., and Rechberger, H. Comparative Goal-Oriented Assessment of Conventional and Alternative Sewage Sludge Treatment Options. Waste Manag 30,6 (2010): 1043-1056.

Lin, T.-C., et al. Co2 Emissions from a Steel Mill and a Petro-Chemical Industry. Aerosol and Air Quality Research (2012).

Liu, B., Wei, Q., Zhang, B., and Bi, J. Life Cycle Ghg Emissions of Sewage Sludge Treatment and Disposal Options in Tai Lake Watershed, China. Sci Total Environ 447 (2013): 361-369.

Liu, Q., et al. Life Cycle Assessment of an Industrial Symbiosis Based on Energy Recovery from Dried Sludge and Used Oil. Journal of Cleaner Production 19,15 (2011): 1700-1708.

Lundin, M., Olofsson, M., Pettersson, G. J., and Zetterlund, H. Environmental and Economic Assessment of Sewage Sludge Handling Options. Resources, Conservation and Recycling 41,4 (2004): 255-278.

Ma, S.-h., Wen, Z.-g., Chen, J.-n., and Wen, Z.-c. Mode of Circular Economy in China's Iron and Steel Industry: A Case Study in Wu'an City. Journal of Cleaner Production 64 (2014): 505-512.

MAC. Thai Agricultural Standard: Compost. 2005. Available: http://www.acfs.go.th/standard/download/eng/compost.pdf.

Maugans, C., Howdeshell, M., and De Haan, S. "Update: Spent Caustic Treatment." Hydrocarbon Process 2010: 61-65.

Mccoy, J. N., and Stell, R. C. "Process for Decoking a Furnace for Cracking a Hydrocarbon Feed." Houston, 2008. Vol. 20080207974 20080207974 vols.

Menikpura, S. N., Gheewala, S. H., and Bonnet, S. Framework for Life Cycle Sustainability Assessment of Municipal Solid Waste Management Systems with an Application to a Case Study in Thailand. Waste Manag Res 30,7 (2012): 708-719.

MIGA. Environmental Guidelines for Petrochemicals Manufacturing: Multilateral Investment Guarantee Agency, 2000.

Mills, N., Pearce, P., Farrow, J., Thorpe, R. B., and Kirkby, N. F. Environmental & Economic Life Cycle Assessment of Current & Future Sewage Sludge to Energy Technologies. Waste Manag 34,1 (2014): 185-195.

MOE. The World in Transition, and Japan's Efforts to Establish a Sound Material-Cycle Society Office of Sound Material-cycle Society Waste Management and Recycling Department, Ministry of the Environment, Government of Japan 2008.

Moharamned, N., Aghajani, M., Atabi, F., and Azarkamand, S. Petrochemical Supply Chainâ□™S Share in Emission of Green House Gases, Case Study: Shazand Petrochemical Complex. American Journal of Environmental Sciences 9,4 (2013): 334-342.

Mohundro, E. L. "Overview on C2 and C3 Selective Hydrogenation in Ethylene Plants." 2003. Vol. 2011.

Mokhtarani, B. Report: Future Industrial Solid Waste Management in Pars Special Economic Energy Zone (Pseez), Iran. Waste Management & Research 24,3 (2006): 283-288.

Monte, M. C., Fuente, E., Blanco, A., and Negro, C. Waste Management from Pulp and Paper Production in the European Union. Waste Manag 29,1 (2009): 293-308.

Moriguchi, Y. Material Flow Indicators to Measure Progress toward a Sound Material-Cycle Society. Journal of Material Cycles and Waste Management 9,2 (2007): 112-120.

Mosier, A., Hutchinson, G., Sabey, B., and Baxter, J. Nitrous Oxide Emissions from Barley Plots Treated with Ammonium Nitrate or Sewage Sludge Journal of Environmental Quality 11,1 (1982): 78-81.

MSTE. "Industrial Wastewater Standards." 3. Ed. T. a. E. Notification of the Ministry of Science. Thailand: Ministry of Science, Technology and Environment, 1996.

Nucci, B., Puccini, M., Pelagagge, L., Vitolo, S., and Nicolella, C. Improving the Environmental Performance of Vegetable Oil Processing through Lca. Journal of Cleaner Production 64 (2014): 310-322.

Ondrey, G. "Causes and Prevention of Packing Fires." Chemical Engineering Magazine 2007.

PCD. Overview on Waste Management in Thailand. 2012. Pollution Control Department. Available: http://infofile.pcd.go.th/mgt/Overview_waste.pdf?CFID=19195763&CFTOKEN=14293228.

Perugini, F., Mastellone, M. L., and Arena, U. A Life Cycle Assessment of Mechnical and Feedstock Recycling Options for Management of Plastic Packaging Wastes Environmental Progress 24,2 (2005): 137-154.

Phumpradab, K., Gheewala, S. H., and Sagisaka, M. Life Cycle Assessment of Natural Gas Power Plants in Thailand. The International Journal of Life Cycle Assessment 14,4 (2009): 354-363.

Plasynski, S. I., and Chen, Z. Y. "Review of Co2 Capture Technologies and Some Improvement Opportunities." the 220th ACS National Meeting. Washington DC: ACS Division of Fuel Chemistry 2000. 644-649 Vol. 45.

Plaza, C., Xu, Q., Townsend, T., Bitton, G., and Booth, M. Evaluation of Alternative Landfill Cover Soils for Attenuating Hydrogen Sulfide from Construction and Demolition (C&D) Debris Landfills. J Environ Manage 84,3 (2007): 314-322.

Pombo, F. R., Magrini, A., and Szklo, A. An Analysis of Water Management in Brazilian Petroleum Refineries Using Rationalization Techniques. Resources, Conservation and Recycling 73 (2013): 172-179.

PRéConsultants. Simapro | World’s Leading Lca Software. 2013. Available: http://www.pre-sustainability.com/simapro. 3 March 2013.

PTIT. The Preparation of Comparative Information Industry to Increase Competitiveness of Petrochemical Industry: Phase 2: Petroleum Institute of Thailand, Petroleum Institute of Thailand Office and Industrial of Economics, Ministry of Industry, 2009.

PTIT. Ptit’s Petrochemical Product Classification. Bangkok, Thailand Petroleum Institute of Thailand 2012.

Punsuwannakhi, S. "The Integrated of Industrial Waste Management." Bangkok Industrial Waste Management Bureau, 2012.

Rives, J., Rieradevall, J., and Gabarrell, X. Lca Comparison of Container Systems in Municipal Solid Waste Management. Waste Manag 30,6 (2010): 949-957.

Roberts, B. H. The Application of Industrial Ecology Principles and Planning Guidelines for the Development of Eco-Industrial Parks: An Australian Case Study. Journal of Cleaner Production 12,8-10 (2004): 997-1010.

Roland, C. The Concept of Clean Technology. Clean Technology 1,1 (1995): 34-46.

Sakai, S.-i., et al. International Comparative Study of 3r and Waste Management Policy Developments. Journal of Material Cycles and Waste Management 13,2 (2011): 86-102.

Sarker, M., Rashid, M. M., Molla, M., and Abundant High-Density Polyethylene (Hdpe-2) Turns into Fuel by Using of Hzsm-5 Catalyst. J Funda Renew Energ App 1 (2011): 1-12.

SCIeco. Example of Accepting Waste for Burn as Co-Material in Cement Kilns. 2011. SCIeco Service Corporation Available: http://www.scieco.co.th/accept_waste.php.

Simboli, A., Taddeo, R., and Morgante, A. Analysing the Development of Industrial Symbiosis in a Motorcycle Local Industrial Network: The Role of Contextual Factors. Journal of Cleaner Production 66 (2014): 372-383.

Simões, C. L., Pinto, L. M., Simoes, R., and Bernardo, C. A. Integrating Environmental and Economic Life Cycle Analysis in Product Development: A Material Selection Case Study. The International Journal of Life Cycle Assessment 18,9 (2013): 1734-1746.

Star-Grit. Chemical/Physical Properties. 2009. Available: http://www.stargrit.in/chemical.html. March 25 2013.

Stuart, R. Command and Control Regulation. 2006. Available: http://www.eoearth.org/article/Command_and_control_regulation. Oct 29 2011.

Suh, Y.-J., and Rousseaux, P. An Lca of Alternative Wastewater Sludge Treatment Scenarios. Resources, Conservation and Recycling 35 (2002): 191–200.

Tarantini, M., Buttol, P., and Maiorino, L. An Environmental Lca of Alternative Scenarios of Urban Sewage Sludge Treatment and Disposal. Thermal Science 11,3 (2007): 153-164.

Taylor, R. Coping with Pollution: Dealing with Waste. Global Environmental Issues. Ed. F. Harris. Singapore John Wiley & Sons, Ltd. , 2012.

Tchobanoglous, G., Theisen, H., and Vigil, S. Integrated Solid Waste Management. Singapore: McGraw-Hill, 1993.

Themelis, N. J., and Ulloa, P. A. Methane Generation in Landfills. Renewable Energy 32,7 (2007): 1243-1257.

UNEP. "Industry and Environment " 8th International High-level Seminar on Sustainable Consumption and Production. Mexico the United Nations Environment Programme, 2004. Vol. 27.

UNEP. "Industry and Environment." Sixth International High-level Seminar Montreal. Canada: United Nations Environment Programme, 2001. Vol. 24. Ed. U. N. E. Programme.

UNEP. Review of Progress, Constraints and Policy Challenges with Regard to the Implementation of International, Regional and National Commitments: Waste Management (Hazardous and Solid Wastes). Bangkok: United Nations Environment Programme, 2009.

UNEP. State of Waste Management in South East Asia. 2012. United Nations Environment Programme. Available: http://www.unep.or.jp/Ietc/Publications/spc/State_of_waste_Management/7.asp2012.

UNFCCC. Cge Ghg Inventory Handbook (Nai), Consultative Group of Experts on National Communications from Parties Not Included in Annex I to the Convention (Cge): United Nations Framework Convention on Climate Change, 2013.

Usapein, P., and Chavalparit, O. Options for Sustainable Industrial Waste Management toward Zero Landfill Waste in a High-Density Polyethylene (Hdpe) Factory in Thailand. Journal of Material Cycles and Waste Management (2013).

Usapein, P., and Chavalparit, O. "Solid Waste Management for the Petrochemical Industry in Thailand by Using 3r's Option." 4th AUN/SEED-Net Regional Conference on Global Environment and Seminar of NRCT-JSPS Asian Core Program The Emerald Hotel, Bangkok, Thailand, 2012. 113-116.

USEPA. Definition of Volatile Organic Compounds (Voc). 2009. U.S. Environmental Protection Agency. Available: http://www.epa.gov/ttn/naaqs/ozone/ozonetech/def_voc.htm. 12 December 2011.

USEPA. Life Cycle Assessment (Lca). 2012. United States Environmental Protection Agency Available: http://www.epa.gov/nrmrl/std/lca/lca.html. August 3 2013.

Valderrama, C., et al. Comparative Lca of Sewage Sludge Valorisation as Both Fuel and Raw Material Substitute in Clinker Production. Journal of Cleaner Production 51 (2013): 205-213.

Van Berkel, R. Evolution and Diversification of National Cleaner Production Centres (Ncpcs). Journal of Environmental Management 91,7 (2010): 1556-1565.

Varoonchotikul, T. "Lca Related Issues & Calculation of Carbon Footprint." Bangkok Thailand Greenhouse Gas Management Organization (Public Organization) (TGO), 2011.

Vitcas. Fire Bricks. 2011. Available: http://www.vitcas.com/fire-bricks. April 12 2014.

Vlasopoulos, N., Memon, F. A., Butler, D., and Murphy, R. Life Cycle Assessment of Wastewater Treatment Technologies Treating Petroleum Process Waters. Sci Total Environ 367,1 (2006): 58-70.

Wittmaier, M., Langer, S., and Sawilla, B. Possibilities and Limitations of Life Cycle Assessment (Lca) in the Development of Waste Utilization Systems - Applied Examples for a Region in Northern Germany. Waste Manag 29,5 (2009): 1732-1738.

Wu, H.-q., Shi, Y., Xia, Q., and Zhu, W.-d. Effectiveness of the Policy of Circular Economy in China: A Dea-Based Analysis for the Period of 11th Five-Year-Plan. Resources, Conservation and Recycling 83 (2014): 163-175.

Yoshida, H., Christensen, T. H., and Scheutz, C. Life Cycle Assessment of Sewage Sludge Management: A Review. Waste Manag Res 31,11 (2013): 1083-1101.

Zaman, A. U. Identification of Key Assessment Indicators of the Zero Waste Management Systems. Ecological Indicators 36 (2014a): 682-693.

Zaman, A. U. Measuring Waste Management Performance Using the ‘Zero Waste Index’: The Case of Adelaide, Australia. Journal of Cleaner Production 66 (2014b): 407-419.

Zamorano, M., Grindlay, A., Molero, E., and Rodríguez, M. I. Diagnosis and Proposals for Waste Management in Industrial Areas in the Service Sector: Case Study in the Metropolitan Area of Granada (Spain). Journal of Cleaner Production 19,17-18 (2011): 1946-1955.

Zhou, J. H., Zhao, J. G., and Li, P. "Study Progress on the Cleaner Production and Environmental Management System of Iso14000." International Conference on Future BioMedical Information Engineering, 2009. 202-203.

APPENDICES

APPENDIX A

The calculation of data in Chapter IV

The calculation of landfill waste reduction

$$\%Landfill\ waste\ reduction = \frac{(LF_{initial} - LF_{final})}{LF_{initial}} \times 100$$

where, LFinitial and LFfinal are the amount of landfill waste before applied with 3R option and the amount of landfill waste after applied with 3R option, respectively.

The calculation of environmental impact

The details of calculated greenhouse gas reduction are described in the following section.

Type of waste: Bio-sludge

Option: Co-composting bio-sludge to produce fertilizer

Amount of avoided fertilizer production = Amount of bio-sludge × yield of fertilizer production (%)

$GHG_{reduction}$ = Amount of avoided fertilizer production × GHG emission factor of N-fertilizer

Amount of waste (tons)	Yield of fertilizer production (%)	Amount of avoided fertilizer production (tons)	Emission factor of N-fertilizer (kg CO2 eq/kg fertilizer)	GHG reduction (tons CO2 eq/year)
122.13	20	24.43	2.6	63.51

Type of waste: Molecular sieve, copper slag, refractory brick

Option: Burn inorganic wastes as raw material in cement kiln

Type of waste	Amount of waste (tons)	Composition
Molecular sieve	463.19	Al_2O_3 26.4%, SiO_2 31.06, H_2O 20.96%, K_2O 16.22%, Na_2O 5.35%
Copper slag	116.53	Al_2O_3 3.01%, Fe_2O_3 55%, SiO_2 35%
Refractory brick	118.57	Al_2O_3 37%, Fe_2O_3 1.6%, SiO_2 61%
Total inorganic waste	698.29	

Amount of clay substituted =

$$\frac{132.46\ tonnes\ of\ Al2O3}{} \times \frac{1000\ kg\ of\ clay}{397\ kg\ of\ Al2O3} \times \frac{1000kg\ of\ Al2O3}{1\ ton\ of\ Al2O3} \times \frac{1\ ton\ of\ clay}{1000\ kg\ of\ clay} =$$

333.65 tons of clay

$GHG_{reduction}$ = Amount of avoided clay production × GHG Emission factor of clay

Amount of inorganic waste (tons)	Amount of avoided clay production (tons)	GHG emission factor of clay (kg CO2 eq/kg clay)	GHG reduction (tons CO2 eq/year)
698.29	333.65	0.0028	0.92

Type of waste: Sludge

Option: Burn sludge as alternative energy in cement kiln

$$386.51\ tonnes\ of\ sludge\ \times 10\%\ (\%\ of\ solid\ content) \times \frac{18513\ MJ}{ton\ sludge} \times \frac{ton\ bituminous\ coal}{23865\ MJ}$$

= 29.98 ton bituminous coal

$GHG_{reduction}$ = Amount of avoided bituminous coal × GHG Emission factor of bituminous coal

Amount of sludge (tons)	Amount of avoided bituminous coal (tons)	GHG emission factor of bituminous coal (kg CO2 eq/kg bituminous coal)	GHG reduction (tons CO2 eq/year)
386.51	29.98	2.94	88.06

APPENDIX B

The calculation of data in Chapter V

The calculation of GHG emission for producing 1 ton of clinker product

Bituminous coal:

The required energy for producing 1 ton of clinker is equal to 3,000 MJ/ton clinker

The heating value of bituminous coal is equal to 23,865 MJ/ton coal

Therefore, the ratio of required coal to produce 1 ton of clinker is equal to

$$\frac{3000}{1}\frac{MJ}{ton\ clinker}\times\frac{1}{23865}\frac{ton\ coal}{MJ}=\frac{0.1257}{}\frac{ton\ coal}{ton\ clinker}$$

The emission factor of greenhouse gas emission from 1 ton of burning bituminous coal production is 2.937 × 10^3 kg CO_2 eq. (Data obtained from eco-invent database)

GHG emission from bituminous coal =

$$\frac{0.1257}{}\frac{ton\ coal}{ton\ clinker}\times\frac{2.937\times10^3}{}\frac{kg\ CO2}{1\ ton\ coal}=369.18\ kg\ CO_{2-eq}$$

Waste polymer:

The heating value of bituminous coal is equal to 43,000 MJ/ton polymer waste

Therefore, the ratio of required coal to produce 1 ton of clinker is equal to

$$\frac{3000}{1}\frac{MJ}{ton\ clinker}\times\frac{1}{43000}\frac{ton\ waste\ polymer}{MJ}=\frac{0.07}{}\frac{ton\ waste\ polymer}{ton\ clinker}$$

The emission factor of greenhouse gas emission from 1 ton of burning polyethylene is 2.992 × 10^3 kg CO_2 eq. (Data obtained from eco-invent database)

GHG emission from waste polymer =

$$\frac{0.07}{}\frac{ton\ waste\ polymer}{ton\ clinker}\times\frac{2.992\times10^3}{}\frac{kg\ CO2}{1\ ton\ waste\ polymer}=209.46\ kg\ CO_{2-eq}$$

Box/Packaging:

The heating value of kraft paper is equal to 16890 MJ/ ton kraft paper

Therefore, the ratio of required coal to produce 1 ton of clinker is equal to

$$\frac{3000}{1}\frac{MJ}{ton\ clinker}\times\frac{1}{16890}\frac{ton\ kraft\ paper}{MJ}=\frac{0.18}{}\frac{ton\ kraft\ paper}{ton\ clinker}$$

The emission factor of greenhouse gas emission from 1 ton of burning Kraft paper is 20 kg CO_2 eq. (Data obtained from eco-invent database)

GHG emission from waste polymer =

$$\frac{0.18}{}\frac{ton\ paper\ waste}{ton\ clinker}\times\frac{20}{}\frac{kg\ CO2}{1\ ton\ paper\ waste}=3.60\ kg\ CO_{2-eq}$$

The other impacts such as Ozone depletion, Acidification, and Aquatic eutrophication EP(N) are also calculated by using the same method. The emission factor is presented in Table B1.

Table B.1 the environmental impact from each type of fuel

Impact categories	Bituminous coal	Waste polymer	Box/Packaging	Unit (per ton waste)
Ozone depletion	3.69×10^{-5}	1.14×10^{-6}	14.72×10^{-7}	kgCFC11eq
Acidification	379	3.72	4.80	m^2
Aquatic eutrophication EP(N)	0.63	0.04	0.06	Kg N

APPENDIX C

The calculation of data in Chapter VI

Scenario of sludge disposal

Landfill (Scenario 0)

$8\ C_{35}H_{59}O_{24}N_4S + 94\ H_2O \Longrightarrow 137\ CH_4 + 32\ NH_3 + 143\ CO_2 + 8\ H_2S$

Molecular weight sludge	=	951	g/mol

Ideal CH_4 emission	=	288	kg CH_4 * 0.77 (%VS)	= 222 kg CH_4
Ideal H_2S emission	=	35.8	kg H_2S * 0.77 (%VS)	= 27.5 kg H_2S
Ideal NH_3 emission	=	71.5	kg NH_3 * 0.77 (%VS)	= 55.1 kg NH_3
Ideal CO_2 emission	=	827	kg CO_2 * 0.77 (%VS)	= 637 kg CO_2

In this study, we assumed that the methane collection efficiency is 40% which directly emitted to the environment; therefore, the residue of methane which permeated through soil and emitted to the environment is 60% of total methane generation. The percentage of methane oxidation by soil is 60% and the characterisation value of methane is 27.75.

Amount of methane directly emitted to the environment	= 88.7 kg CH_4
Amount of residue methane in landfill	= 133 kg CH_4

Table C.1 The amount of methane generation from landfill scenario

Categories	Value (kg $CO_{2\text{-eq}}$)
1. Amount of CO_2 directly emitted to the environment	88.7 * 27.75 = 2,463
2. Amount of CH_4 permeated through soil and emitted to the environment	133 * (100-60%) *27.75 = 1,478
3. Amount of CO_2 from methane oxidation	79.9
4. Amount of CO_2 from sludge anaerobic process	637
Total	4,657

Landfill with gas utilization by producing electricity (Scenario 1)

Table C.2 Sensitivity analysis of methane collection efficiency

CH_4 collection efficiency	CH_4 collection (kg)	CH_4 residue (kg)	CH_4 oxidation by soil	CH_4 emit to atmosphere (kg)	CO_2 from CH_4 oxidation (kg)	GWP from LF (kg CO2 eq)
40%	88.7	133	0.60	53.2	79.9	1,557
60%	133	88.7	0.60	35.5	53.2	1,038
90%	200	22.2	0.60	8.87	13.3	260

Table C.3 CO_2 emission from CH_4 combustion of each methane collection efficiency

Methane collection efficiency	CO_2 from CH_4 combustion	Unit
40%	244	kg CO_2
60%	366	kg CO_2
90%	549	kg CO_2

Table C.4 Global Warming Potential (GWP) of each methane collection efficiency

Methane collection efficiency	Total GWP	Unit
40%	1,801	kg CO_2 eq
60%	1,404	kg CO_2 eq
90%	809	kg CO_2 eq

Calculation of electricity production

Efficiency for electricity production	40%	(Cuéllar and Webber, 2008)
Heating value of methane	55.53	MJ/kg (Bhattacharjee, 2014)

Table C.5 The amount electricity production (kWh) of each methane collection efficiency

Methane collection efficiency	Methane collection (kg)	Methane collection (MJ)	Amount of electricity production (kWh)
40%	88.7	4,928	548
60%	133	7,392	821
90%	200	11,087	1,232

Table C.6 Emission factor of electricity production in Thailand (per MWh)

Pollutants	Value (kg)	Source
Carbon monoxide	0.0706	(Phumpradab et al., 2009)
Carbon dioxide	535	
Methane	0.1780	
Nitrogen oxides	1.08	
Dinitrogen monoxide	0.0017	
Sulfur dioxide	0.0077	

Table C.7 Avoided emission from electricity production

Total avoided emission	S1 40%	S1 60%	S1 90%
Carbon monoxide	0.0387	0.0580	0.0870
Carbon dioxide	293	439	659
Methane	0.0974	0.1462	0.2192
Nitrogen oxides	0.5893	0.8839	1.33
Dinitrogen monoxide	0.0009	0.0014	0.0021
Sulfur dioxide	0.0042	0.0063	0.0094

Table C.8 Avoided mid-point analysis from electricity production

Impact categories	S1 40%	S1 60%	S1 90%
Respiratory inorganic	0.0754	0.1131	0.1696
Terrestrial Nutri/Acid	3.24	4.86	7.29
Acidification	0.4167	0.6251	0.9376
Global warming	296	444	666

Use of bio-sludge as a conventional fuel substitute in cement kiln (Scenario 2)

$$4C_{35}H_{59}O_{24}N_4S + 171O_2 ==> 140CO_2 + 4SO_2 + 16NO_2 + 118H_2O$$

Molecular weight sludge = 951 g/mol

Ideal SO_2 emission = 67.3 kg SO_2

Ideal NO_2 emission = 193 kg NO_2

Ideal CO_2 emission = 1,619 kg CO_2

In this study, we assumed that the fuel gas from sludge combustion will be pass desulfurization unit to remove sulfur dioxide gas before discharge to the environment. The reaction to extract sulphur dioxide was assumed to be as follow:

$$SO_2 + 0.5H_2O + CaCO_3 \longrightarrow CaSO_3.0.5H_2O + CO_2$$

Table C.9 Sensitivity analysis of scrubber efficiency

Scrubber efficiency	CO_2 from desulfurization (kg CO_2)	Total CO_2 emission
50%	23.1	1,642
70%	32.4	1,652
90%	41.6	1,661

Calculation avoided lignite coal

Heating value of lignite coal = 3,600 kcal/kg (Brokerage, 2013)

= 15,072 MJ/ton lignite coal

Heating value of Sludge = 18,513 MJ/ton sludge

Ratio of substitute lignite coal per sludge

= 1.23 ton lignite coal / ton sludge

Table C.10 Emission factor of lignite coal combusted in industrial boiler :per kg (Combustion)

Impact category	Unit	Lignite coal, combusted in industrial boiler/US
Carcinogens	kg C_2H_3Cl eq	0.0003
Non-carcinogens	kg C_2H_3Cl eq	0.0076
Respiratory inorganics	kg PM2.5 eq	0.0018
Aquatic ecotoxicity	kg TEG water	33.0
Terrestrial ecotoxicity	kg TEG soil	11.8
Terrestrial acid/nutri	kg SO_2 eq	0.0475
Aquatic acidification	kg SO_2 eq	0.0183
Aquatic eutrophication	kg PO_4 P-lim	0.0000
Global warming	kg CO_2 eq	2.41

Source: (EcoinventCentre, 2009)

Table C.11 Emission factor of lignite coal combusted in industrial boiler :per kg (Extraction)

Impact category	Unit	Lignite, at mine/RER U
Carcinogens	kg C_2H_3Cl eq	0.0000
Non-carcinogens	kg C_2H_3Cl eq	0.0001
Respiratory inorganics	kg PM2.5 eq	0.0000
Aquatic ecotoxicity	kg TEG water	0.3089
Terrestrial ecotoxicity	kg TEG soil	0.0368
Terrestrial acid/nutri	kg SO_2 eq	0.0002
Aquatic acidification	kg SO_2 eq	0.0001
Aquatic eutrophication	kg PO_4 P-lim	0.0007
Global warming	kg CO_2 eq	0.0137

Source: (EcoinventCentre, 2009)

Table C.12 Avoided emission from lignite coal combusted in industrial boiler: per kg

Impact category	Unit	Avoided emission
Carcinogens	kg C_2H_3Cl eq	0.3908
Non-carcinogens	kg C_2H_3Cl eq	9.33
Respiratory inorganics	kg PM2.5 eq	2.25
Aquatic ecotoxicity	kg TEG water	40,559
Terrestrial ecotoxicity	kg TEG soil	14,467
Terrestrial acid/nutri	kg SO_2 eq	58.3
Aquatic acidification	kg SO_2 eq	22.5
Aquatic eutrophication	kg PO_4 P-lim	0.0007
Global warming	kg CO_2 eq	3,226

Table C.13 Avoided emission from Lignite coal extraction: per kg

Impact category	Unit	Avoided emission
Carcinogens	kg C_2H_3Cl eq	0.0455
Non-carcinogens	kg C_2H_3Cl eq	0.0655
Respiratory inorganics	kg PM2.5 eq	0.0132
Aquatic ecotoxicity	kg TEG water	379
Terrestrial ecotoxicity	kg TEG soil	45.2
Terrestrial acid/nutri	kg SO_2 eq	0.2646
Aquatic acidification	kg SO_2 eq	0.0724
Aquatic eutrophication	kg PO_4 P-lim	0.9024
Global warming	kg CO_2 eq	16.8

Table C.14 Total avoided emission from lignite coal

Impact category	Unit	Avoided emission
Carcinogens	kg C_2H_3Cl eq	0.4363
Non-carcinogens	kg C_2H_3Cl eq	9.40
Respiratory inorganics	kg PM2.5 eq	2.26
Aquatic ecotoxicity	kg TEG water	40,939
Terrestrial ecotoxicity	kg TEG soil	14,512
Terrestrial acid/nutri	kg SO_2 eq	58.6
Aquatic acidification	kg SO_2 eq	22.5
Aquatic eutrophication	kg PO_4 P-lim	0.9031
Global warming	kg CO_2 eq	3,243

Recycling bio-sludge as raw material for fertilizer production (Scenario 3)

To calculate the emission from fertilizer production, the data from (Cederberg, 2004; Flodman, 2002; Johansson et al., 2008; Mosier et al., 1982) were used as the emission factors.

Table C.15 The direct emission from producing fertilizer by using sludge as co-material

Type of pollutants	GWP (kg CO2 eq.)	AP (kg SO2 eq.)	EP (kg NO3 eq.)
Methane to air	160	-	-
N_2O to air as N	65	-	-
Ammonia to air as N	-	1.9	3.6
Nitrate to water as N	-	-	33

Source: (Cederberg, 2004; Flodman, 2002; Johansson et al., 2008; Mosier et al., 1982).

Calculate avoided fertilizer production

Ratio of substitute N fertilizer and P fertilizer per ton of sludge is provided below (Liu et al., 2013).

0.21 ton N fertilizer ==> 1 ton sludge

0.23 ton P fertilizer ==> 1 ton sludge

Table C.16 Emission factor of N fertilizer production

Impact category	Unit	Value
Carcinogens	kg C_2H_3Cl eq	0.0008
Non-carcinogens	kg C_2H_3Cl eq	0.0575
Respiratory inorganics	kg PM2.5 eq	0.0016
Aquatic ecotoxicity	kg TEG water	326
Terrestrial ecotoxicity	kg TEG soil	0.5613
Terrestrial acid/nutri	kg SO_2 eq	0.0298
Aquatic acidification	kg SO_2 eq	0.0201
Aquatic eutrophication	kg PO_4 P-lim	0.0000
Global warming	kg CO_2 eq	1.33

per: kg N fertilizer

Source: (EcoinventCentre, 2007)

Table C.17 Emission factor of P fertilizer production

Impact category	Unit	Value
Carcinogens	kg C_2H_3Cl eq	0.0299
Non-carcinogens	kg C_2H_3Cl eq	0.3288
Respiratory inorganics	kg PM2.5 eq	0.0016
Aquatic ecotoxicity	kg TEG water	569
Terrestrial ecotoxicity	kg TEG soil	10.2
Terrestrial acid/nutri	kg SO_2 eq	0.0270
Aquatic acidification	kg SO_2 eq	0.0188
Aquatic eutrophication	kg PO_4 P-lim	0.0670
Global warming	kg CO_2 eq	0.3711

per: kg P fertilizer

Source: (EcoinventCentre, 2007)

Table C.18 Avoided emissions from N fertilizer

Impact category	Unit	Total
Carcinogens	kg C_2H_3Cl eq	0.1618
Non-carcinogens	kg C_2H_3Cl eq	12.1
Respiratory inorganics	kg PM2.5 eq	0.3393
Aquatic ecotoxicity	kg TEG water	68,414
Terrestrial ecotoxicity	kg TEG soil	118
Terrestrial acid/nutri	kg SO_2 eq	6.25
Aquatic acidification	kg SO_2 eq	4.21
Aquatic eutrophication	kg PO_4 P-lim	0.0044
Global warming	kg CO_2 eq	280

Table C.19 Avoided emissions from P fertilizer

Impact category	Unit	Total
Carcinogens	kg C_2H_3Cl eq	6.8794
Non-carcinogens	kg C_2H_3Cl eq	75.6
Respiratory inorganics	kg PM2.5 eq	0.3655
Aquatic ecotoxicity	kg TEG water	130,876
Terrestrial ecotoxicity	kg TEG soil	2,336
Terrestrial acid/nutri	kg SO_2 eq	6.21
Aquatic acidification	kg SO_2 eq	4.33
Aquatic eutrophication	kg PO_4 P-lim	15.4
Global warming	kg CO_2 eq	85.4

Table C.20 Avoided emissions from fertilizer

Impact category	Unit	Total
Carcinogens	kg C_2H_3Cl eq	7.04
Non-carcinogens	kg C_2H_3Cl eq	87.7
Respiratory inorganics	kg PM2.5 eq	0.7048
Aquatic ecotoxicity	kg TEG water	199,290
Terrestrial ecotoxicity	kg TEG soil	2,454
Terrestrial acid/nutri	kg SO_2 eq	12.5
Aquatic acidification	kg SO_2 eq	8.54
Aquatic eutrophication	kg PO_4 P-lim	15.42
Global warming	kg CO_2 eq	365

Scenario of copper slag disposal

Landfill (Scenario 0)

Table C.21 Emission factor of copper slag disposed of by landfill

Impact category	Unit	Disposal, copper slag, 0% water, to landfill/ton
Carcinogens	kg C2H3Cl eq	0.0124
Non-carcinogens	kg C2H3Cl eq	0.0161
Respiratory inorganics	kg PM2.5 eq	0.0067
Aquatic ecotoxicity	kg TEG water	3,767
Terrestrial ecotoxicity	kg TEG soil	2.95
Terrestrial acid/nutri	kg SO2 eq	0.1643
Aquatic acidification	kg SO2 eq	0.0245
Aquatic eutrophication	kg PO4 P-lim	0.0005
Global warming	kg CO2 eq	2.83

Source: (EcoinventCentre, 2007)

Burn in cement kiln (Scenario 1)

Table C.22 Emission factor of copper slag disposed of by burning in cement kiln

Impact category	Unit	Burn in cement kiln/ton
Carcinogens	kg C2H3Cl eq	0.0115
Non-carcinogens	kg C2H3Cl eq	0.0029
Respiratory inorganics	kg PM2.5 eq	0.0066
Aquatic ecotoxicity	kg TEG water	15.1
Terrestrial ecotoxicity	kg TEG soil	2.67
Terrestrial acid/nutri	kg SO2 eq	0.1616
Aquatic acidification	kg SO2 eq	0.0236
Aquatic eutrophication	kg PO4 P-lim	0.0002
Global warming	kg CO2 eq	2.39

Source: (EcoinventCentre, 2007)

Scenario of refractory brick disposal

Landfill (Scenario 0)

Table C.23 Emission factor of refractory brick disposed of by landfill

Impact category	Unit	Disposal, refractory brick, 0% water, to landfill/ton
Carcinogens	kg C2H3Cl eq	4.06
Non-carcinogens	kg C2H3Cl eq	38.3
Respiratory inorganics	kg PM2.5 eq	0.1047
Aquatic ecotoxicity	kg TEG water	378,647
Terrestrial ecotoxicity	kg TEG soil	940
Terrestrial acid/nutri	kg SO2 eq	3.21
Aquatic acidification	kg SO2 eq	0.5605
Aquatic eutrophication	kg PO4 P-lim	0.0060
Global warming	kg CO2 eq	309

Source: (EcoinventCentre, 2007)

Burn in cement kiln (Scenario 1)

Emission factor of refractory brick burned in cement kiln was used the same value of copper slag which appeared in Table C.22.

Scenario of contaminated container disposal

Landfill (Scenario 0)

Table C.24 Emission factor of contaminated container disposed of by landfill

Impact category	Unit	polyethylene, 0.4% water, to landfill/ton
Carcinogens	kg C2H3Cl eq	0.0266
Non-carcinogens	kg C2H3Cl eq	0.0898
Respiratory inorganics	kg PM2.5 eq	0.0120
Aquatic ecotoxicity	kg TEG water	293
Terrestrial ecotoxicity	kg TEG soil	6.24
Terrestrial acid/nutri	kg SO2 eq	0.2853
Aquatic acidification	kg SO2 eq	0.0433
Aquatic eutrophication	kg PO4 P-lim	0.0038
Global warming	kg CO2 eq	58.5

Source: (EcoinventCentre, 2007)

Reused contaminated container (Scenario 1)

Table C.25 Environmental impact of reuse contaminated container

Impact category	Unit	Reuse contaminated container/ton
Carcinogens	kg C2H3Cl eq	-303
Non-carcinogens	kg C2H3Cl eq	-5.89
Respiratory inorganics	kg PM2.5 eq	-0.8611
Aquatic ecotoxicity	kg TEG water	-19,146
Terrestrial ecotoxicity	kg TEG soil	-45.5
Terrestrial acid/nutri	kg SO2 eq	-20.7
Aquatic acidification	kg SO2 eq	-6.26
Aquatic eutrophication	kg PO4 P-lim	-0.0075
Global warming	kg CO2 eq	-1,474

Note: Calculated from the data of (Rives et al., 2010).

Recycling contaminated container (Scenario 2)

Table C.26 Environmental impact of recycling contaminated container

Impact category	Unit	Total
Carcinogens	kg C2H3Cl eq	-266
Non-carcinogens	kg C2H3Cl eq	-5.16
Respiratory inorganics	kg PM2.5 eq	-0.7409
Aquatic ecotoxicity	kg TEG water	-16,767
Terrestrial ecotoxicity	kg TEG soil	-35.9
Terrestrial acid/nutri	kg SO2 eq	-17.6
Aquatic acidification	kg SO2 eq	-5.42
Aquatic eutrophication	kg PO4 P-lim	-0.0056
Global warming	kg CO2 eq	-1,163

Note: Calculated from the data of (Perugini et al., 2005).

Calculation damage categories

Table C.27 The effect of pollutants in each sub compartment

Pollutants	Sub compartment	Respiratory inorganics	Aquatic acidification	Terrestrial acid/nutri	Global warming	Non-carcinogens	Carcinogens	Terrestrial ecotoxicity	Aquatic ecotoxicity	Aquatic eutrophication
Methane	Air	●			●					
Nitrogen dioxide	Air	●	●	●						
Carbon dioxide	Air				●					
Sulfur dioxide	Air	●	●	●						
Hydrogen sulfide	Air		●			●				
Ammonia	Air	●	●	●		●		●	●	
Cadmium	Air					●	●	●	●	
Chromium	Air					●	●	●	●	
Cr(III)	Air									
Cr(VI)	Air					●	●	●	●	
Cr(Ion)	Air					●	●			
Cu	Air					●		●	●	
Hg	Air					●		●	●	
Pb	Air					●		●	●	
As	Air					●	●	●	●	
COD	Water									●
Suspend solid	Water									
Total nitrogen	Water									
Hg	Water					●		●	●	
Cr(III)	Water									
Cr(VI)	Water					●			●	

Table C.27 The effect of pollutants in each sub compartment (continued)

Pollutants	Sub compartment	Respiratory inorganics	Aquatic acidification	Terrestrial acid/nutri	Global warming	Non-carcinogens	Carcinogens	Terrestrial ecotoxicity	Aquatic ecotoxicity	Aquatic eutrophication
Cd	Water									
Cd (Ion)	Water					●	●	●	●	
As	Water									
As (Ion)	Water					●	●		●	
Ni	Water									
Ni (Ion)	Water					●			●	
Cu	Water									
Cu (Ion)	Water					●			●	
Pb	Water					●			●	
Fe (Ion)	Water									
Fe	Water									
Mn	Water									
NO3	Water									
Nitrogen, total	Soil									
Potassium	Soil									●
Phosphorus	Soil									
As	Soil					●	●	●	●	
Cd	Soil					●		●	●	
Cr	Soil					●		●	●	
Cu	Soil					●		●	●	
Hg	Soil					●		●	●	
Pb	Soil					●		●	●	

Table C.28 Mid-point reference substance (Humbert et al., 2012)

Classes	Midpoint reference substance	Air	Soil	Water	Total	Unit
Human Health						
Carcinogenic effects	Ethylene, chloro- (into air, only carcinogenic effects)	1.83E+10	1.07E+09	2.31E+08	1.96E+10	[kgeq/y]
Non-carcinogenic effects	Ethylene, chloro- (into air, only carcinogenic effects)	5.76E+10	1.58E+10	1.27E+09	7.46E+10	[kgeq/y]
Respiratory (inorganic)	PM2.5 (into air)	3.79E+09			3.79E+09	[kgeq/y]
Ecosystem Quality						
Aquatic ecotoxicity	Triethylene glycol (into water, only aquatic effects)	1.07E+12	5.31E+14	5.30E+13	5.85E+14	[kgeq/y]
Terrestrial ecotoxicity	Triethylene glycol (into soil, only effects through water into soil)	1.01E+12	5.17E+14	4.03E+06	5.18E+14	[kgeq/y]
Terrestrial acidification/nutrification	SO_2 (into air)	1.36E+11			1.36E+11	[kgeq/y]
Aquatic acidification	SO_2 (into air)	2.85E+10	0.00E+00	0.00E+00	2.85E+10	[kgeq/y]
Aquatic eutrophication (P-limited watershed)	PO_4--- (into water)	0.00E+00	4.41E+09	6.85E+08	5.09E+09	[kgeq/y]

Table C.29 Damage categories factors (Humbert et al., 2012)

Classes	Damage (endpoint) unit	Air	Soil	Water	Total	
Human Health						
Carcinogenic effects	DALY	5.14E+04	3.00E+03	6.48E+02	5.50E+04	[DALY/y]
Non-carcinogenic effects	DALY	1.61E+05	4.43E+04	3.56E+03	2.09E+05	[DALY/y]
Respiratory (inorganic)	DALY	2.65E+06			2.65E+06	[DALY/y]
Ecosystem Quality						
Aquatic ecotoxicity	PDF.m2.y	5.35E+07	2.67E+10	2.66E+09	2.94E+10	[PDF.m2.y/y]
Terrestrial ecotoxicity	PDF.m2.y	8.01E+09	4.09E+12	3.19E+04	4.10E+12	[PDF.m2.y/y]
Terrestrial acidification/nutrification	PDF.m2.y	1.42E+11			1.42E+11	[PDF.m2.y/y]
Aquatic acidification	PDF.m2.y	2.52E+08			2.52E+08	[PDF.m2.y/y]
Aquatic eutrophication (P-limited watershed)	PDF.m2.y	0.00E+00	1.59E+10	2.48E+09	1.84E+10	[PDF.m2.y/y]

APPENDIX D

The calculation of data in Chapter VII

The example of calculated 3R indicator for HDPE case study plant.

Table D.1

Option	Quantity (tons)	Total LF waste generation (tons)	Category	Score of 3R potential (3)
Burning stabilizer bag in cement kiln	26.24	31.06	Recycle	1
Recycling contaminated container	1.83	31.06	Recycle	1

Table D 2 Point of main category

No.	Option	Economic (3)	Environmental impact score (3)		
			GHG (1)	HZW (1)	LCA (1)
1	Burning stabilizer bag in cement kiln	0.0	1.0	1.0	0.8
2	Recycling contaminated container	0.0	1.0	1.0	1.0

Note: Score 1 means the selected option shows positive impact to the factory when compared with landfill option. Score 0 means the selected option shows negative impact to the factory when compared with landfill option.

Table D 3 Point of sub-category in LCA

GWP	AP	RI	TAN	AEP	AE	TE	Car	Non-carci	Total
0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.00	0.00	0.77
0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.99

Note: Score 0.11 means the selected option shows positive impact to the factory when compared with landfill option. Score 0.00 means the selected option shows negative impact to the factory when compared with landfill option.

Total score of HDPE case study plant:

Option 1: (1+0+1+1+0.8)*26.24/31.06 = 3.18

Option 2: (1+0+1+1+1)*1.83/31.06 = 0.24

Total score of 3RI for HDPE case study plant = 3.18+0.24 = 3.42

VITA

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List of published research papers:

Usapein P, Chavalparit O. 2014. Options for sustainable industrial waste management toward zero landfill waste in a high-density polyethylene (HDPE) factory in Thailand. Journal of Material Cycles and Waste Management 16(2), pp.373-383.

Usapein P, Chavalparit O. 2014. Development of Sustainable Waste Management toward Zero Landfill Waste for the Petrochemical Industry in Thailand using a Comprehensive 3R Methodology: A Case Study. Waste Management & Research, first published on May 13, 2014 as doi:10.1177/0734242X14533604.