รายงานวิจัยฉบับสมบูรณ์

โครงการการประเมินผลกระทบทางสิ่งแวดล้อมตลอดวัฏจักรชีวิต และผลกระทบทางเศรษฐกิจและสังคมของการใช้ประโยชน์จากเถ้าแกลบที่เกิดจากโรงไฟฟ้าแกลบ

โดย จิตติมา ประสาระเอ

เมษายน 2561

สัญญาเลขที่ TRG5880074

รายงานวิจัยฉบับสมบูรณ์

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จิตติมา ประสาระเอ

มหาวิทยาลัยมหาสารคาม

สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัยและต้นสังกัด

Abstract (บทคัดย่อ)

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Project Title : Environmental and Socio-Economic Assessment of Utilization of Rice Husk Ash Generated from Rice Husk Based Power Plants
(ชื่อโครงการ) การประเมินผลกระทบทางสิ่งแวดล้อมตลอดวัฏจักรชีวิต และผลกระทบทางเศรษฐกิจและสังคมของการใช้ประโยชน์จากเถ้าแกลบที่เกิดจากโรงไฟฟ้าแกลบ

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This research assesses the environmental and socio-economic performances of selected rice husk ash use options, both export and local uses. The sustainability indicators assessed include climate change, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, fossil depletion, total net profit (TNP) and total value added (TVA), employment generation and income of workers involved in production processes. The results for export options show that, for amorphous silica rice husk ash, using it in rubber indsutry is more environmentally friendly than using it in construction industry as it can help reduce great impacts by substituting rice husk ash for commercial filler. For crystalline silica rice husk ash, using it in steel industry is better for the environment. This option can help to reduce impacts by replacing fire brick with rice husk ash. All export rice husk use options have socio-economic benefits for the rice husk based power plants and the domestic transportation sector. The results for local use options show that using the ash as soil conditioner is better both in terms of environmental and socio-economic aspects. Moreover, recommendations for policy makers have been provided. For example, the rice husk based power plants should be provided with assistance to find markets for exporting the ash. This way will help manage the ash more sustainable. In addition, use of amorphous rice husk ash in rubber and construction industries should also be promoted in Thailand.

งานวิจัยนี้มีวัตถุประสงค์เพื่อประเมินผลกระทบต่อสิ่งแวดล้อม และผลกระทบทางเศรษฐกิจและสังคมของทางเลือกการใช้ขี้เถ้าแกลบจากโรงฟ้า ทั้งการส่งออกและการนำไปใช้ในท้องถิ่น ตัวชี้วัดความยั่งยืนที่ประเมินได้แก่ การเปลี่ยนแปลงสภาพภูมิอากาศ การทำให้เป็นกรดบนพื้นดิน ปรากฏการณ์ยูโทรฟิเคชั่นน้ำจืด ความเป็นพิษต่อมนุษย์ การเกิดอนุมูลอิสระทางเคมี การสร้างอนุภาค สารพิษในระบบนิเวศบก สารพิษในน้ำจืด การลดลงของเชื้อเพลิงฟอสซิล รวมกำไรสุทธิ รวมมูลค่าเพิ่ม และรายได้ของคนงานที่เกี่ยวข้องในกระบวนการผลิต ผลการศึกษาพบว่า สำหรับการส่งออกขี้เถ้าแกลบที่มีซิลิกาแบบไม่มีรูปร่าง การใช้เป็นวัสดุทดแทนฟิลเลอร์ในอุตสาหกรรมยางจะเป็นมิตรกับสิ่งแวดล้อมมากกว่าการใช้ในอุตสาหกรรมก่อสร้าง เนื่องจากสามารถลดผลกระทบได้มากกว่า สำหรับขี้เถ้าแกลบที่มีซิลิกาแบบผลึก การใช้ในอุตสาหกรรมเหล็กเป็นทางเลือกที่ดีต่อสิ่งแวดล้อมมากกว่า ตัวเลือกนี้สามารถช่วยลดผลกระทบโดยการทดแทนอิฐทนไฟด้วยขี้เถ้าแกลบ ทั้งนี้ ทางเลือกการใช้ขี้เถ้าแกลบส่งออกทั้งหมดมีผลประโยชน์ทางเศรษฐกิจและสังคมต่อโรงไฟฟ้าจากแกลบและภาคการขนส่งภายในประเทศ ผลการศึกษาพบว่าทางเลือกการใช้งานขี้เถ้าแกลบในท้องถิ่น แสดงให้เห็นว่าการใช้ขี้เถ้าแกลบเป็นวัสดุปรับปรุงดินเป็นทางเลือกที่ดีทั้งด้านสิ่งแวดล้อมและด้านเศรษฐกิจและสังคม นอกจากนี้ยังมีการเสนอข้อเสนอแนะสำหรับผู้กำหนดนโยบาย ตัวอย่างเช่นโรงไฟฟ้าที่ใช้แกลบควรได้รับความช่วยเหลือในการหาตลาดสำหรับการส่งออกขี้เถ้าแกลบ วิธีนี้จะช่วยในการจัดการขี้เถ้าแกลบที่ยั่งยืนมากขึ้น นอกจากนี้ควรมีการส่งเสริมการใช้ขี้เถ้าแกลบที่มีซิลิกาแบบไม่มีรูปร่างในอุตสาหกรรมยางและอุตสาหกรรมก่อสร้างในประเทศด้วย

Keywords : Life Cycle Assessment; Socio-Economic Assessment; Rice Husk Ash
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Summary

This report presents the environmental, economic and social performances of different existing and potential uses of rice husk ash generated from the power plants. It begins with introduction (chapter 1). Chapter 2 reviews sustainability characteristics of the uses of rice husk ash from power plants. It also reviews how rice husk ash is produced from different power generation technologies. Characteristics of rice husk ash are affected by different factors such as sources, preparation methods and combustion technologies. Different forms of rice husk ash, amorphous and crystalline, suit different applications. Ash from moving grate technology is suggested for use as adsorbent while that from fluidized bed is suggested for use as filler in polymeric composites and in the synthesis of innovative ceramic compounds. The ash from suspension fired technology is suggested for use in the construction industry and zeolite production. In addition to technical viability, using rice husk ash to substitute conventional products helps gain both environmental and economic benefits. Despite claiming sustainable applications of rice husk ash, many research papers report only technical performances of the products. This chapter draws out sustainability characteristics of different rice husk ash applications using the “triple bottom line” framework. Potential reduction of greenhouse gas emissions, cost saving and employment generation of rice husk ash use options have been investigated. Results from the review suggest that using the ash to replace charcoal is the most sustainable option when comparing with other alternatives such as Portland cement, commercial silica and lime. This option could help to reduce GHG up to 1,005 kg CO_{2eq}/t product, to save cost up to 8,000 THB/t product, as well as to help generate employment for about 5 person-years/M THB spent in the sector.

Chapter 3 discusses current situation of rice husk ash generated in the power plants and its uses within the Thai context. Moreover, it presents the environmental, economic and social performances of main uses of rice husk ash generated from the power plants using life cycle approach. Main indicators such as Climate change, Terestrial acidification, Freshwater eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Fossil depletion, total net profit (TNP) and total value added (TVA), employment generation and income of workers involved in production processes studied are examined. Chapter 4 draws conclusions for this research and provides recommendations to improve sustainability of management of rice husk ash generated from the power plants.

Chapter1: Introduction

Rationale

Thailand produces a large amount of rice. In recent year, Thailand produced more than 39 million tonnes of rice (Office of Agricultural Economics, 2014). Rice husk is a co-product of rice products generated in the rice milling process. This husk accounts for about 23 percent of the total paddy weight (rice crop weight). The husk has traditionally been used as an energy source in the rice mills themselves. However, there is still some surplus rice husk remaining unused in the mills. Rice husk is considered one of the main sources of biomass in Thailand as it has a large available amount and is collectable from the mills.

More recently, the Thai government has promoted the use of biomass for energy purposes to substitute for fossil fuel consumption and to reduce the environmental impacts caused by using fossil fuels (Amornkosit, 2007; Coovattanachai, 2006; Lertsuridej, 2004). Therefore, rice husk, which is one of the main sources of biomass in Thailand, has been widely used in electricity generation on a commercial scale. This is indicated by increased numbers in rice husk fuelled power plants registered (Energy Policy and Planning Office, 1999, 2014).

Rice husk ash is a waste generated when burning rice husk in a boiler. Rice husk is used as a fuel in the boiler to generate steam for generator turbine to provide electricity. This ash from the rice husk based power plants has already been utilized in different applications. For instance, to be exported (use in steel industry), use in cement and concrete industry, use as soil conditioner and use as substrate for planting (Kanjanawarawanich, 2012). However, not much research on environmental, economic and social impacts of rice husk ash applications have been found. Some studies about environmental and economic assessments of rice husk ash applications were found (Berkin, 2008; Lertsatitthanakorn et al., 2009; Mendes Moraesa et al., 2010; Thepnoo, 2006). Nevertheless, only limited applications were studied. This proposed research will cover wider rice husk ash use alternatives to examine.

Apart from environmental and economic aspects of the rice husk ash applications, social aspect should also be considered. This will provide better information for decision making. The previous work of the researcher (Prasara-A, 2010) attempted to assess environmental impacts of different uses of rice husk ash generated from the rice husk based power plants in Thailand.

However, only limited rice husk ash applications were included, and only environmental aspect has been considered. The economic and social aspects have not yet been assessed.

Life Cycle Assessment (LCA) is a tool used in environmental management. It is used to assess the environmental impacts of product or service. It considers all life cycle stages of the product/service (cradle to grave). The life cycle stages include raw material acquisition, production process, transportation and distribution, use, recycle/reuse and disposal (Thailand Environment Institute (TEI), 2004). Considering impacts in all life cycle stages makes it a useful tool. LCA is widely used to compare the environmental impacts of different products/services to help in decision making.

This research will assess the environmental, economic and social performances of different existing uses of rice husk ash generated from the power plants using life cycle approach. Main environmental and socio-economic indicators such as Climate change, Terestrial acidification, Freshwater eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Fossil depletion, total net profit (TNP) and total value added (TVA), employment generation and income of workers involved in production processes studied will be examined.

Objectives

The overall aim of this project is to assess the environmental, economic and social performances of different main uses of rice husk ash generated from the power plants using life cycle approach. To achieve this aim, specific objectives to be tackled are:

1) Investigate current situation of utilization of rice husk ash generated from rice husk power plants in Thailand

2) Assess the environmental and socio-economic impacts of the selected rice husk ash applications

3) Provide recommendations about sustainable uses of rice husk ash generated from rice husk power plants in Thailand for policy makers.

Outputs/Outcomes

Outputs from this project are:

Journal articles:

Prasara-A, J., Gheewala, S.H., 2017. Sustainable utilization of rice husk ash from power plants: A review. Journal of Cleaner Production 167, 1020-1028.

Conference Presentations:

Prasara-A, J. & Gheewala, S. H., 2015, *Sustainable Utilization of Ash Generated from Rice Husk Based Power Plants*, paper presented to the 5th International Conference on Green and Sustainable Innovation (ICGSI 2015), Dusit Thani Pattaya Hotel, Pattaya, Thailand, 8 – 10 November.

Outcome from this project is:

- Policy recommendations about sustainable management of rice husk ash generated from rice husk power plants.

Scope of study

Environmental, economic and social performance indicators include Climate change, Terestrial acidification, Freshwater eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Fossil depletion, total net profit (TNP) and total value added (TVA), employment generation and income of workers involved in production processes. Both primary and secondary data are used in this study. Where data from sites are required, sites are selected from the northeastern region as this area has the largest rice planting area in the nation.

Functional Unit

Functional unit set for this study is 1,000 tonnes of rice husk ash processed. As the comparison for all products have to be done based on the same basis. This functional unit will be used as a comparison basis for different alternatives.

System boundary

System boundary for this study is presented in Figure. 1. The system boundary covers sugar cane cultivation, transportation, sugar milling, and production processes of co-products uses. The system boundary also avoids conventional products of the co-products examined.

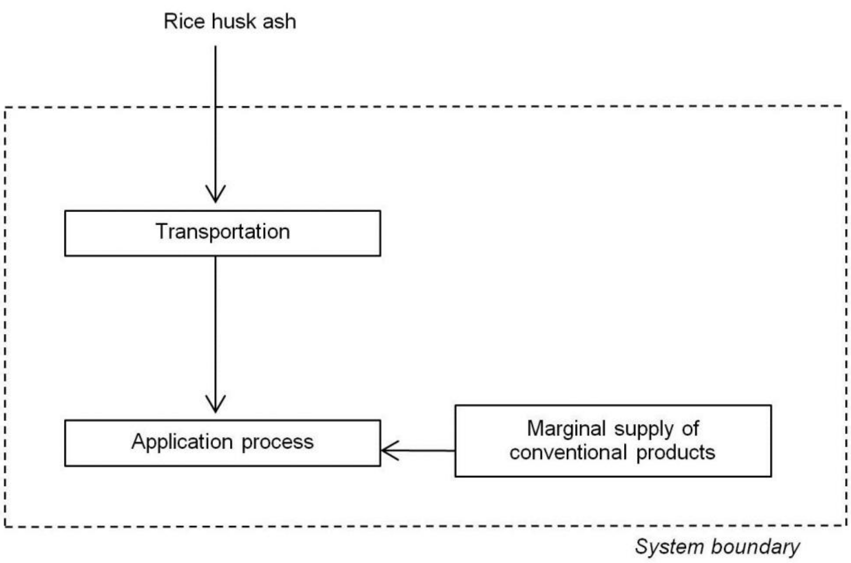

Figure 1 System boundary for this study

Research approach

Environmental assessment

In this study, the environmental impacts of rice husk ash uses will be analyzed using Life Cycle Assessment (LCA). Main environmental indicators to be assessed are global warming potential, resource depletion, land use change, acidification, eutrophication and ecotoxicity.

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) will be use to assess the environmental impacts of the selected rice husk ash applications. In cases co-products are used in other systems, system expansion approach will be used to help avoid allocation for the co-products in the LCI modeling (Ekvall and Finnveden, 2001).

LCA consists of 4 main stages: goal definition, inventory analysis, impact assessment and interpretation.

1) Goal definition: The goal for this LCA study is to analyze the environmental impacts of the selected rice husk ash applications. Functional unit set for this LCA study is 1,000 tonnes of rice husk ash consumed.

2) Inventory analysis: LCI data include data about inputs such as materials and energy consumption and outputs such as emissions released in the processes studied. LCI data will be collected from different sources such as in rice husk based power plants, factories involved in using rice husk ash, reports, articles, LCI databases in LCA software etc. In some case, emissions data may be obtained by laboratory analysis if they are not collected and reported by the factories/sectors. In this case, the researcher plans to hire professionals for the analysis to get the emissions data (to be used in LCA study).

To assess the environmental performances of the rice husk ash uses, their environmental impacts will be assessed against that of their conventional products. This will provide net environmental impacts of the rice husk ash uses. The rice husk ash uses selected to study may include: use as insulator in steel industry (export), use as substitute material in concrete industry (export), use as feedstock in soil substrate industry, and use as soil conditioner in rice fields.

3) Impact assessment: SimaPro software and ReCiPe 2008 impact assessment method will be used in the impact assessment. Impact categories to analyze are global warming potential, resource depletion, land use change, acidification, eutrophication, ecotoxicity, and human toxicity. These impacts will be all analyzed using SimaPro software.

4) Interpretation: To response to the goal of the study, the environmental impacts of different selected rice husk ash applications will be compared. Process contribution and sensitivity analysis will also be undertaken. Sensitivity analysis will be conducted to see how assumptions made and choices of impact assessment methods influence the overall results. Process contribution will be undertaken to find the processes that play significant role in the overall impacts and data quality of these processes will be checked.

Socio-economic assessment

This research aims at finding socio-economic performances of different uses of rice husk ash from the rice husk based power plants. Socio-economic indicators to be analyzed are total net profit (TNP), total value added (TVA), employment generation and incomes of workers involved in production processes studied. These indicators were chosen to assess because they could indicate how much the rice husk ash applications studied could help in socio-economic improvement.

Total net profit (TNP)

Total net profit is the summation of the net profit gain from all main and co-products. The calculation can be done by subtracting total production costs from the returns gained from the enterprise. Returns in the enterprise include revenue from sales of both the main and co-products. Total costs include values of all inputs and supplies required in the production process. It also include value of intermediate inputs, labour costs (including wages and salaries), various taxes and duties charged in the production process, and other costs items (SAGISAKA et al., 2010).

The formulas to be used for calculation of TNP are as followed (SAGISAKA et al., 2010):
Total Returns = Sales from Primary Output + Sales from By-products
Total Costs = Value of Material Inputs Used + Labour Costs + Overhead Costs
Overhead Costs = Taxes and Duties + Interest + Depreciation
Net Profit = Total Returns – Total Costs

Total value added (TVA)

The TVA is the summation of all the value-added in each enterprise. This includes personnel remuneration, taxes and duties earned by the government from the enterprises and the entrepreneur’s net profit.

The formula to be used for the calculation of TVA is as followed (SAGISAKA et al., 2010):
Total Value Added = Total Net Profit + Personnel Remuneration + Tax Generated

Data about values of all inputs and supplies, labor costs, taxes and duties charged in the production processes, and other costs items required in the production processes of the selected rice husk ash applications are expected to be collected from the factories involved. Selling prices of the products generated from the processes studied could be collected from the factories themselves as well as from the Department of Internal Trade.

Employment generation

Employment generation will be calculated per functional unit set (1,000 tonnes of rice husk ash consumed) and will be reported in full-time equivalent (FTE) jobs per year. This will be investigated in work hours required to process 1,000 tonnes of rice husk ash in production processes under study. It will then be converted to FTE jobs in a year by dividing by total hours worked by a full time worker in 1 year (2080 hours). Data to be collected for employment calculation are numbers of employees of the factories involved and production rates of the products generated in the processes studied. These could be collected from the factories. If data are not available in any case, they are expected to be collected from National Statistical Office. Indirect employment will be estimated using percentage of indirect employment from Silalertruksa et al. (2012).

Income of workers

Income of workers may help to accelerate other social sub-indicators such as change in education, health, gender upliftment, living standard, etc. Therefore, this research will compare incomes of workers involved in different rice husk ash applications examined. Data about incomes of the workers involved in the processes studied will be collected by interviews with the workers involved and from the factories. If data are not available in any case, they are expected to be collected from National Statistical Office.

Research framework of this study is shown in Figure 2.

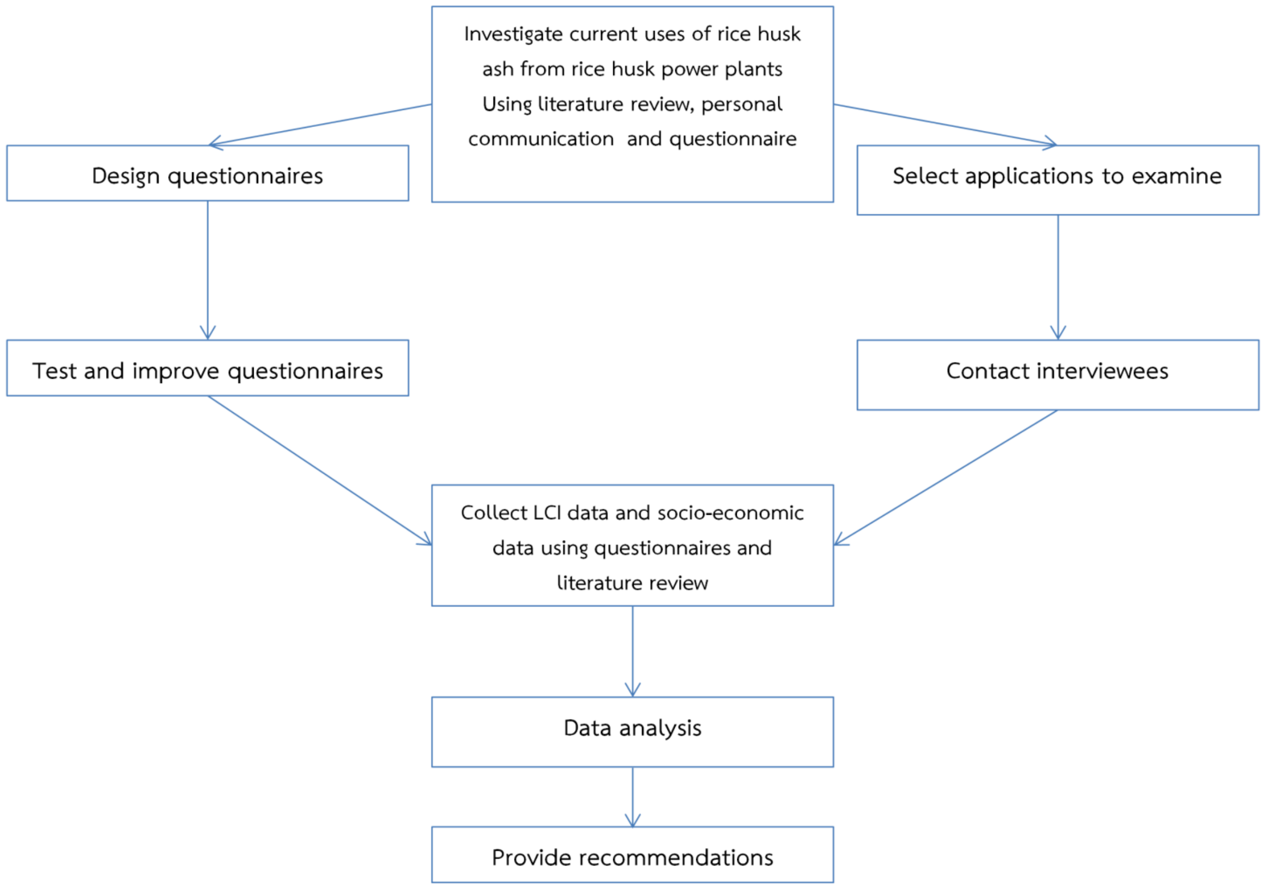

Figure 2 Reseach framework

Outline of report

Chapter 2 starts with reviweing sustainability characteristics of potential rice husk ash uses both locally and internationally. In this chapter key environmental, economic, and social aspects of rice husk ash uses are discussed. Chapter 3 presents the environmental, economic, and social performances of selected rice husk ash uses to examine. This chapter aims to indentify sustainbility issues for utilization of rice husk ash from rice husk based power plants within the Thai context. Chapter 4 provides conclusions and recommendations from this research project.

Chapter 2: A review of sustainability of rice husk ash utilization

Introduction

Sustainable development is an important matter worldwide and Thailand is also focusing on the sustainability issue in different sectors as appearing also in its sustainable development goals (United Nations, 2015). To help achieve sustainability, the “triple bottom line” is often used. This framework promotes taking into consideration all environmental, economic and social aspects (Elkington, 2002). To avoid looking at a single dimension of sustainability in isolation like many conventional sustainability assessments, this framework was developed to assess multiple dimensions of sustainability, i.e. environment, economy and society. This framework is useful for decision makers to identify consequences of activities’ impacts on all environmental, economic and social dimensions. This would provide supporting information to help policy makers in choosing actions that lead to a sustainable society.

Biomass energy is the most important alternative energy source for Thailand. As an agricultural based economy, Thailand has abundant biomass resources. Biomass is considered relatively clean compared with fossil fuels (Sajjakulnukit et al., 2005). Accordingly, the Thai government has promoted the use of biomass for energy purposes to substitute fossil fuels, in order to help conserve non-renewable resources and reduce environmental impacts (Amornkosit, 2007; Coovattanachai, 2006; Lertsuridej, 2004). The largest source of biomass in Thailand is agricultural residues, i.e. bagasse, rice husk, palm oil wastes, and wood residues (Sajjakulnukit et al., 2005).

Rice is the most important agricultural product of Thailand. It is both staple food for Thailand’s population and the main export product of the country. Thailand produces a large amount of rice. In 2014, Thailand produced about 38 million tonnes of rice (Office of Agricultural Economics, 2014). Rice husk is a co-product of rice products generated in the rice milling process, accounting for about 23 percent of the total paddy weight (rice crop weight) (Prasertsan and Sajjakulnukit, 2006). The husk has sometimes been used as an energy source in the rice mills themselves. Rice husk is considered one of the major biomass feedstocks in Thailand as it has a large available amount and is conveniently collectable from the mills (Sajjakulnukit et al., 2005).

Most rice husk in Thailand is currently being used to produce electricity on a commercial scale. This is indicated by increased numbers in rice husk fuelled power plants registered (Energy Policy and Planning Office, 1999, 2014). Based on production capacities of the rice husk fuelled power plants registered, more than 6 million tonnes of rice husk (which accounts for nearly 70 percent of the total rice husk generated annually) is being used to produce electricity (Energy Regulatory Commission, 2015).

Rice husk is used as a fuel in the boiler to generate steam for generator turbine to provide electricity. Rice husk ash is a waste generated when burning rice husk in a boiler. There are several potential uses of rice husk ash from power plants as reviewed in Pode (2016) and Kumar et.al. (2013). However, those previous reviews only deal with possibilities of using rice husk ash in different applications with regards to technical viability. The sustainability aspects of the rice husk ash uses have not yet been investigated.

Proper management of rice husk ash from rice husk based power plants is essential. To help promote sustainable development, there is a need to find sustainable ways of using this ash. This review extracts sustainability performances of different rice husk ash applications in environmental, economic and social aspects. In addition, it identifies gaps for future research. This chapter provides useful information for policy makers involved in rice husk based power plant sector.

Material and methods

Literature search

The Scopus database was used to support the literature search for this review. Major well-known bibliometric information sources are the Web of Science, Scopus and Google Scholar. Among these, Scopus is the largest source offering citation abstract and database of peer-reviewed literature. Scopus includes scientific journal articles, books and papers from conference proceedings. Moreover, a study of Gavel and Iselid (2008) revealed that there is a large match between the citation search results from the Web of Science and Scopus databases.

Screening process

There are several keywords used to search for literature. The authors first used the keyword "rice husk ash", the results came out with 1,808 references published from 1977-2016 from several areas of study. The authors then attempted to narrow down the search results using different keywords: rice husk ash/sustainable/sustainability/green product/eco-friendly/environmental friendly/environmental/economic/socio-economic/social.

Selection of literature

The abstracts of all references found from the screening process were read to see if those studies were related to sustainability assessment of rice husk ash uses. The full-texts of the references found to be relevant were accessed using available online databases. The references selected for review were those with the terms used in the screening process; the terms being included either in the article title, abstract or keywords of the references. Final selection of literature consisted of 21 references which were then used to review the sustainability characteristics of rice husk ash applications.

Sustainability assessment of rice husk ash applications from literature

Following the "triple bottom line" framework, all the selected references were read in detail to extract results on environmental, economic and social aspects of the rice husk ash applications. To ease comparison of sustainability performances across different rice husk ash use options, attempt was made to find results on same indicators and units for different options. In case the results found from the selected references were not in the same units, extra analyses on environmental, economic and social aspects of the rice husk ash applications were conducted by the authors. This is to have results for same indicators and same units which will allow the comparison of sustainability performances of different rice husk ash use options leading to useful recommendation.

Rice husk ash and its uses

This section describes how rice husk ash is generated in the power production. Different technologies for converting rice husk to electricity are discussed. Moreover, it describes rice husk ash characteristics and potential applications of the ash classified by types of rice husk ash.

Power and rice husk ash generation

At present, combustion is the most commonly used technology for rice husk fuelled power generation. However, other potential technologies such as gasification and pyrolysis are also available. Therefore, the main current and potential technologies, i.e. combustion, gasification and pyrolysis were selected to discuss in this chapter.

Combustion

Combustion is a thermochemical process that converts fuel into a hot flue gas which is then used in steam turbines or steam engines to produce heat, steam or electricity (Dinkelbach, 2000). Combustion technology is well established and several Thai rice husk based power plants use it in their production (Energy Policy and Planning Office, 2011).

Rice husk is used as a fuel in the boiler furnace of a power plant. There are three main boiler types used in rice husk fuelled power plants; i.e. stoker, suspension fired and fluidized bed boilers. The stoker boiler is the most common type used among the Thai biomass power plants (Witchakorn and Bundit, 2004). Rice husk is burned differently in different types of boiler furnaces. In stoker boiler furnaces, rice husk is rested on a grate and burned while moving through the furnace. In a suspension fired boiler, the husk is ground before being ejected to burn in the combustion chamber. In the fluidized bed system, the husk is burned in a turbulent bed of hot inert material (Bridgwater et al., 2002).

In general, the rice husk fuelled power plant consists of water pre-treatment, boiler and electricity generator units. For those using suspension fired boilers, a rice husk grinder unit is also installed. Rice husk is burned in the furnace to produce hot flue gas which is then used to heat up pre-treated water in the boiler to generate steam. The high pressure and temperature steam drives the blades of the steam turbine that are connected to an electricity generator. Some of the electricity generated is used internally in the plant and the surplus is transmitted to the grid. The excessive steam released from the turbine is then condensed into water, which is recycled in the boiler (Chungsangunsit et al., 2010). The process diagram for rice husk fuelled power generation using combustion system is shown in Figure 3.

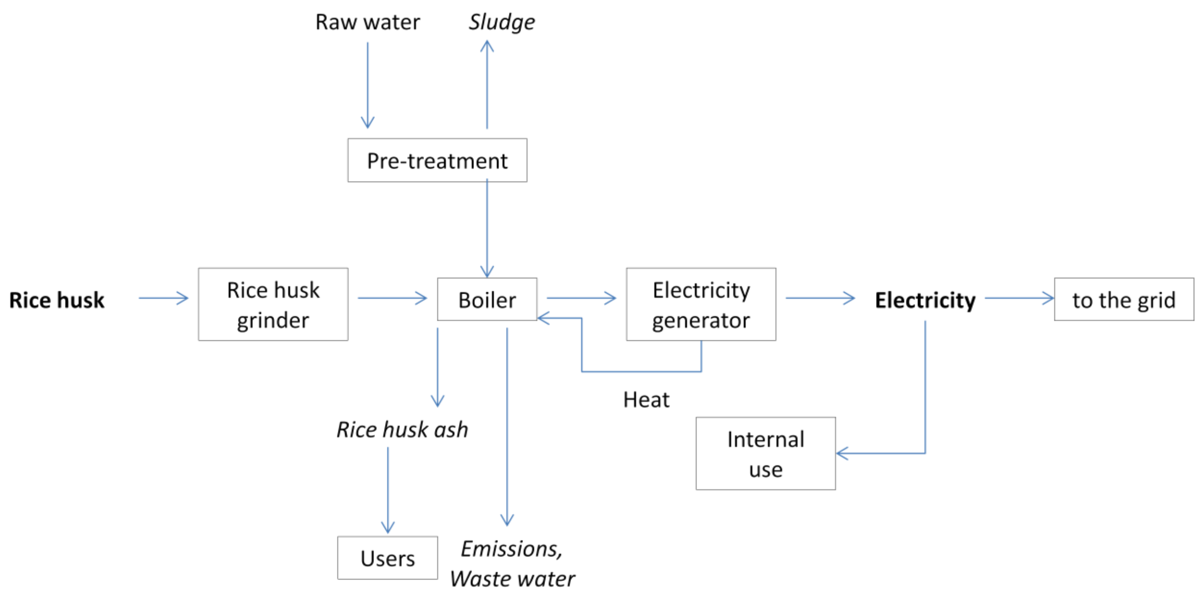

Figure 3 Process diagram for rice husk fuelled power generation using combustion system

Rice husk fuelled power plants release two forms of the rice husk ash, bottom ash and fly ash, which are collected separately. The bottom ash is collected at the base of the furnace whereas the fly ash is captured by the air treatment system. In most cases, the rice husk ash can be easily collected except in the fluidized bed furnace, where the bottom ash is mixed with the bed material when removed (Thepnoo, 2006).The emissions generated from rice husk combustion in a furnace can be vary slightly with the furnace burning technologies. Emissions and waste generated from rice husk fuelled power production using stoker and suspension fired boilers are shown in Table 1.

Table 1 Emissions and waste generated from rice husk fuelled power plants using combustion systems

Parameters	Unit	Stoker boiler[a]	Suspension-fired boiler[b]
Carbon dioxide (CO_2)	kg/MWh	1,690	1,480
Carbon monoxide (CO)	kg/MWh	8.58	1.65
Nitrogen dioxide (NO_2)	kg/MWh	1.31	2.02
Sulfur dioxide (SO_2)	kg/MWh	0.39	1.23
Total Suspended Particulates (TSP)	kg/MWh	0.11	0.67
Rice husk ash	kg/MWh	198	193

Source: [a] Chungsangunsit et al. (2010), [b] Prasara-A (2010)

From Table 1, it is seen that CO_2 is the main emission released from rice husk combustion. The differences in quantities of emissions and ash for these two boiler technologies may be caused by different factors, for example, the amount of rice husk consumed, furnace combustion efficiencies and chemical compositions of rice husk. The CO emission from the suspension-fired boiler furnace is lower than that of the stoker one. This may be due to the higher combustion efficiency of the former where rice husk is ground before being air-injected into the furnace. This could help increase the rice husk surface area for combustion, thus increasing combustion efficiency and consequently reducing the amount of rice husk required in the furnace.

Gasification

Gasification is a thermochemical process that converts fuel into a combustible gas. In the gasification process, partial oxygen is supplied to yield the combustible gas or producer gas. The producer gas contains combustible components such as carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). This gas can be used as a fuel in boilers, engines or gas turbines. The advantage of gasification is that the producer gas can be used in prime movers (gas engines, gas turbines, fuel cells) to generate electricity at higher efficiency (Dinkelbach, 2000).

In Thailand, gasification technology for power production from biomass exists. However, it is less widely used in rice husk based power plants as compared to direct combustion. At present, there are few small rice husk based power plants using gasification technology, with power capacities ranging between 20 – 400 kWe. However, they are still in the demonstration stage (Assanee and Boonwan, 2011).

In general, gasification system consists of feed storage, feed drying, gasifier, gas treatment and generator equipment. The rice husk gasification plants in Thailand use gas engines and modified diesel engines to generate electricity. In modified diesel engine, both diesel and producer gas are used to run the generator (Assanee and Boonwan, 2011). There are different configurations of biomass gasifiers. The major configurations are downdraft, updraft, bubbling and circulating fluidized beds. Yet, only the fluidized bed configurations have generating capacities of over 1 MWe (Bridgwater et al., 2002). Process diagram for rice husk fuelled power generation using gasification system is presented in Figure 4.

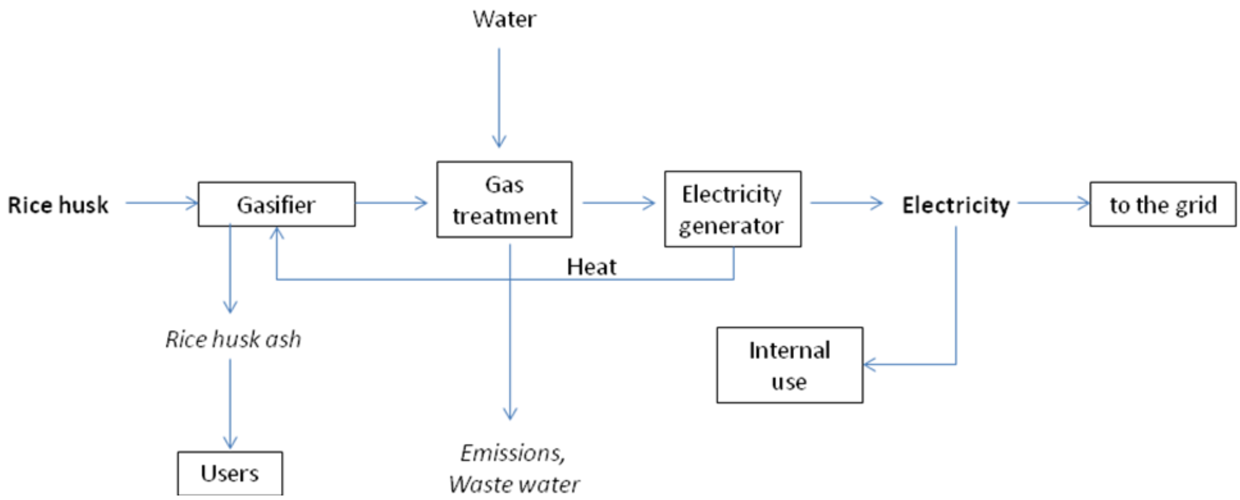

Figure 4 Process diagram for rice husk fuelled power generation using gasification system

An ideal gasification process yields only non-condensable gas (producer gas) and ash residue. However, the gas produced from incomplete gasification is also contaminated with particulates, tars, alkali metals and fuel-bound nitrogen compounds. The ash residue also contains some char (Bridgwater et al., 2002). If water is used in the gas treatment process, waste water is also generated.

Pyrolysis

Pyrolysis is the thermal degradation of biomass in an absence of oxygen. Pyrolysis of biomass produces gas, char and vapour which can be collected as a liquid. This liquid (pyrolysis oil) is a mixture of oil, tar and water (Bridgwater et al., 2002; Dinkelbach, 2000). The amounts and proportion of pyrolysis products generated depend on temperature, heating rate and residence time. Pyrolysis is classified into slow, fast and flash pyrolysis, based on the differences in the above-mentioned factors (Dinkelbach, 2000).

Slow pyrolysis uses lower heating rate, longer residence time and lower temperature. The main product from slow pyrolysis is char; some smaller amounts of oil and gas are also produced when higher temperatures and shorter residence times are used. Fast pyrolysis is developed to yield more oil so the main product produced from fast pyrolysis is pyrolysis oil. Flash pyrolysis is conducted at very high heating rate and temperature, and very short residence time. The main product of flash pyrolysis is gas (Dinkelbach, 2000).

In Thailand, rice husk pyrolysis technology for power production is not yet established. Current research found that fast pyrolysis technology has a potential for power production (Bridgwater et al., 2002; BTG Biomass Technology Group, 2012). In fast pyrolysis process, the main product is pyrolysis oil. The process was designed and tested to maximize the pyrolysis oil for up to 75% wt. on a dry feed basis. A recent study found that maximum pyrolysis oil yield derived from rice husk is up to 50% wt (Fukuda, 2015). Combustion of pyrolysis oil was successfully tested for heat production on a large scale, including co-firing in power plants (Bridgwater et al., 2002; Chiaramonti et al., 2007).

There are several fast pyrolysis reactor configurations available. The fluidized bed configuration is the most popular, mostly with bubbling beds. In general, fast pyrolysis reactors require feed pretreatment to reduce feedstock size. After pretreatment, feed is dried before entering the reactor to reduce moisture content of the feed, and therefore to improve the quality of the oil product. The gas and char produced in the reactor can be used to provide heat back to the pyrolysis process, or it can be exported for feed drying (Bridgwater et al., 2002). Flue gas emission from feed burning is generated in the reactor. Process diagram for rice husk fuelled power generation using pyrolysis system is presented in Figure 5.

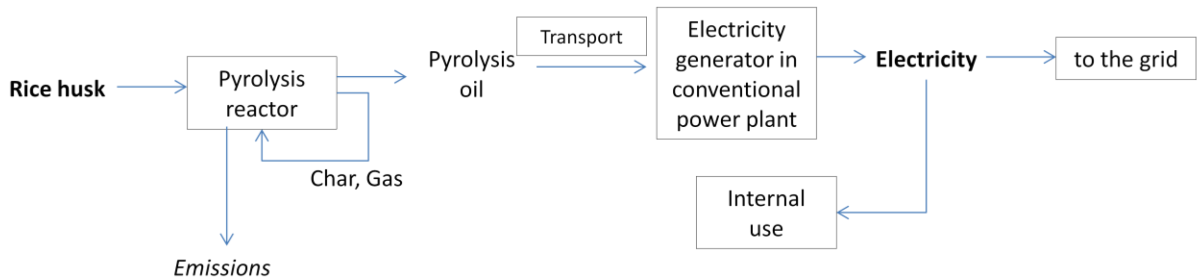

Figure 5 Process diagram for rice husk fuelled power generation using pyrolysis system

Rice husk ash characterization

Rice husk ash is the solid residue from burning rice husk. Its high content of silica (SiO_2) is a very beneficial feature (Muthadhi et al., 2007). The burning condition of rice husk is the key factor affecting how the ash can be used. There are two forms of rice husk ash; i.e. the crystalline and amorphous, which are useful for different applications. While amorphous silica is useful in the cement, construction, and rubber industries (Mehta and Pitt, 1976), crystalline silica is useful for products such as steel, ceramics and refractory bricks (Bronzeoak Ltd., 2003).

Burning time and oxygen presence affect silica form and the surface area of the rice husk ash particles (Hwang and Chandra, 1997). Amorphous silica which has a high surface area, can be produced by using burning temperatures of below 700°C. Amorphous silica can also be obtained by using burning temperatures of lower than 500°C with oxygen over a prolonged stage (Muthadhi et al., 2007). Crystalline silica can be produced with burning temperatures of over 800° C (Hwang and Chandra, 1997).

Power generation technology can affect the characteristics of rice husk ash. A study by Fernandes et al. (2016) shows the chemical composition, loss on ignition, total carbon, specific weight and specific surface area of rice husk ash from different combustion technologies. Their results suggest that the chemical compositions and specific weight of all rice husk ash types investigated are quite similar. The key parameters affected by these combustion techniques are surface area, loss on ignition (LOI), SiO_2 and total carbon content. These affected parameters imply that the ash generated from different combustion technologies is suitable for different applications (Fernandes et al., 2016).

Rice husk ash uses

It has been discussed earlier that different forms of rice husk ash are useful for different applications. This section describes rice husk ash applications based on forms of rice husk ash.

Amorphous rice husk ash

Amorphous silica is reactive, and this feature can be valuable in many applications. For example in concrete production, amorphous rice husk ash is used to improve performance. Strength of the concrete is increased by the chemical reaction between the amorphous silica in rice husk ash and chemicals in Portland cement (Hwang and Chandra, 1997). Several studies from different countries have attempted to produce amorphous silica from rice husk for use in concrete production (Allen, 2005; Kizhakkumodom Venkatanarayanan and Rangaraju, 2015; Maeda et al., 2001; Mehta and Pitt, 1976; Salazar-Carreño et al., 2015).

To help with cost saving, amorphous rice husk ash is also used as substitute material for Portland cement and aggregates in low cost building block production in different countries (Cook et al., 1977; Nair et al., 2006; Stroeven et al., 1999). Amorphous silica from rice husk ash can also be used as cement admixture in the solidification of hazardous wastes (Asavapisit and Macphee, 2007; El-Dakroury and Gasser, 2008). In addition, it can be used as a filler in rubbers/plastics/polymers (Costa et al., 2006; Ishak et al., 1997). However, this application has not yet been tried at an industrial scale. More details of application of amorphous rice husk ash have been described in Prasara-A (2010).

Crystalline rice husk ash

Crystalline silica has a special feature of resistance to burning which is useful in steel, thermal insulator, refractory brick and ceramic production (Gonçalves and Bergmann, 2007; Kurama and Kurama, 2008; Siqueira et al., 2009). More details of application of crystalline rice husk ash have been described in Prasara-A (2010). Moreover, crystalline rice husk ash has been reported to be successfully used at a commercial scale as an insulator in the steel industry (Bronzeoak Ltd., (2003).

Other applications

Apart from the main rice husk ash applications discussed before, some other minor uses and development of several advanced uses of rice husk ash have also been identified in the scientific literature. For example, to produce bio-filter for waste water treatment, as adsorbent, as soil conditioner, as insecticide, in bio-fertilizer production, in silica gel production, as ingredient in lithium batteries, in graphene production, as a composite in polypropylene production, as activated carbon, in zeolite production, in semiconductor production, etc. (Beagle, 1978; Bronzeoak Ltd., 2003; Chareonpanich et al., 2004; International Rice Research Institute, 2016; Kanjanawarawanich, 2012; Pode, 2016; Yam and Mak, 2014).

Applications of rice husk ash generated from power plants

Technology used in rice husk fuelled power plants affects how the ash can be used. Fernandes et al. (2016) suggested that rice husk ash produced from moving grate technology is suitable for use as adsorbent as it has larger specific area than ash from other combustion technologies. On the other hand, the ash from fluidized bed could be used as filler in polymeric composites and in the synthesis of innovative ceramic compounds. The great amount of amorphous silica in rice husk ash from suspension fired technology makes it useful for use as pozzolanic material construction industry and use in zeolite production.

In addition to the combustion technology used in the rice husk power plant, the ash collection technique can also affect the properties of the ash. Thepnoo (2006) showed that combustion technologies and ash collection techniques are key factors affecting the properties of the ash from different rice husk based power plants in Thailand. For example, bulk density and fineness of the rice husk ash from power plants using different combustion technologies and ash collection techniques are relatively different. Moreover, fly ash and bottom ash from the same rice husk power plant have quite different silica content, bulk density and fineness. These factors should also be taken into consideration for rice husk ash management.

Sustainability assessments of rice husk ash applications

This section reviews sustainability assessments of various rice husk ash applications. An attempt has been made to identify all environmental, economic and social impacts of rice husk ash applications reported in the selected references. Data in Table 2 presents how the ash is used in different applications (partial or fully used), their substituted products; and identifies sustainability dimensions (environment, economic and social) considered for each study.

Table 2 Summary of reports on sustainability performances of rice husk ash applications

Application	**Partial/fully used**	**Substituted product**	**Tech. results**	**Env. results**	**Econ. results**	**Soc. results**	**Reference**
High performance concrete	partial	Portland cement	reported	-	reported	-	(Isaia, 2000)
Silica powders	fully	Commercial silica	reported	-	-	-	(An et al., 2010)
Concrete	partial	Portland cement	reported	reported	-	-	(Gursel et al., 2015)
Silica	fully	Sodium carbonate powder and quartz	reported	-	-	-	(Liu et al., 2011)
Activated carbon	fully	Commercial activated carbon	reported	-	-	-	(Liu et al., 2011)
Pb and Zn stabilization	fully	Commercial adsorben	reported	-	-	-	(Bosio et al., 2014)

		ts					
Porous silica	fully	Water glass	reported	-	-	-	(Ahmad-Alyosef et al., 2014)
Soil conditioner	partial	N fertilizer	-	reported	-	-	(Prasara-A and Grant, 2011)
Brick	partial	clay	-	reported	-	-	(Prasara-A and Grant, 2011)
Concrete block	partial	Portland cement	-	reported	-	-	(Prasara-A and Grant, 2011)
Concrete	partial	Portland cement	reported	-	-	-	(Zunino and Lopez, 2016)
Concrete	partial	Portland cement	reported	-	-	-	(Kizhakkumodom Venkatanarayanan and Rangaraju, 2015)
Epoxy coating	partial	Epoxy paint	reported	-	-	-	(Azadi et al., 2011)
Insulator	fully	Commercial insulator	reported	reported	reported	-	(Balo, 2015)
Heat absorbing glass	fully	Sand	reported	-	-	-	(Berkin, 2008)
Brick	partial	Natural sand	reported	-	-	-	(Hwang and Huynh, 2015)
Mortar	partial	Portland	reported	reported	-	-	(Mendes

coating		cement					Moraesa et al., 2010)
Concrete	partial	Portland cement	reported	-	-	-	(Antiohos et al., 2013)
Concrete	partial	Portland cement	reported	-	reported	-	(Khan et al., 2012)
Concrete	partial	Portland cement	reported	reported	-	-	(Rahman et al., 2014)
Rice mill wastewater treatment	fully	Commercial adsorbents	reported	-	-	-	(Kumara et al., 2015)
Pure white silica	fully	Commercial silica	reported	-	-	-	(Kumara et al., 2015)
Bio-char	fully	Charcoal	reported	reported	reported	reported	(Shackley et al., 2012a; Shackley et al., 2012b)
Sand–cement block	partial	Clay brick	reported	-	reported	-	(Lertsatitthanakorn et al., 2009)

Tech. = Technical; Env. = Environmental; Econ. = Economic; Soc. = Social

It is seen that many research papers while claiming sustainable/eco-friendly/environmental-friendly/green applications of rice husk ash only report technical performances of the products. All those reported that rice husk ash is successfully used in different applications considering the technical viability. Some research papers assess both technical and environmental aspects of the products. Only few papers assess technical, environmental and economic aspects of rice husk ash products. Social assessment of rice husk ash products is hardly found.

Environmental aspects

A summary of environmental performances of different rice husk ash applications is presented in Table 3. From results of the selected references, it is difficult to compare environmental performances of different rice husk ash uses. This is because each study uses different indicators for environmental assessments. Moreover, environmental performances of rice husk ash applications from different studies are not assessed on the same basis. Some studies compare environmental performances of rice husk ash uses with that of their conventional products. It was reported that rice husk ash could help reduce environmental impacts when used to substitute conventional products. Some studies compare environmental performances of different alternatives for same rice husk ash product (Balo, 2015). For this, environmental data can be used as supporting information for decision-making.

Table 3 Summary of environmental performances of rice husk ash applications

Application	**Substituted product**	**Indicators**	**Compared with**	**Results**	**Reference**
Concrete	Portland cement	- GWP	Conventional concrete	Use of rice husk ash helps reduce GWP.	(Gursel et al., 2015)
Soil conditioner Brick Concrete block	N fertilizer Clay Portland cement	- Climate change - Ozone depletion - Acidification - Eutrophication - Human toxicity - Photochemical oxidant formation - Particulate matter formation - Ecotoxicity - Land occupation - Water depletion - Metal depletion	Among different rice husk ash use options; soil conditioner, brick, concrete block production and landfill	Use of rice husk ash in concrete block production shows best environmental performance among options investigated.	(Prasara-A and Grant, 2011)

		- Fossil fuel depletion			
Insulator	Commercial insulator	- CO_2 - SO_2	Among four different energy types used (natural gas, fuel-oil, coal, and LPG)	- CO_2 emission varies between 22.25 and 9.97 kg/(m^2yr) - SO_2 emission varies between 19.37 and 0.03 kg/(m^2yr)	(Balo, 2015)
Mortar coating	Portland cement	- Operating situation - Frequency or probability of aspects - Impact occurrence - Severity - Degree of risk.	Conventional mortar	Use of rice husk ash helps reduce environmental impacts.	(Mendes Moraesa et al., 2010)
Concrete	Portland cement	- Carbon footprint	Conventional concrete	Use of rice husk ash helps reduce carbon footprint.	(Rahman et al., 2014)
Bio-char	Charcoal	- Environmental contaminants - Carbon abatement	-	- Environmental contaminants are assessed for use in process improvement - carbon abatement from rice husk char addition is approximately 0.42tCO_2 t^{-1} rice husk	(Shackley et al., 2012a; Shackley et al., 2012b)

Economic and social aspects

A summary of economic performances of different rice husk ash applications is presented in Table 4. Like environmental performance, the economic results from the selected references could not be compared. This is because those studies use different economic indicators. However, it shows that rice husk ash can help save production cost as reported in Isaia (2000). In the study of Balo (2015), payback periods of different options in producing insulator from rice husk ash are assessed. This can be useful for decision makers.

Regarding social aspect, only one study reported social issue of rice husk ash use. Health and safety issues are reported in the study on rice husk char production (Shackley et al., 2012a; Shackley et al., 2012b). It was pointed out that the health impact of concern is exposure to crystalline form of rice husk ash. However, further tests are suggested to determine the extent of amorphous and crystalline portions in rice husk char.

Table 4 Summary of economic performances of rice husk ash applications

Application	Substituted product	Indicator	Compared with	Results	Reference
High performance concrete	Portland cement	Equivalent cost of cement	- Among different mixtures of rice husk ash, cement, fly ash and silica fume	Mixtures with more pozzolans (including rice husk ash) have lower costs.	(Isaia, 2000)
Insulator	Commercial insulator	Payback period	- Among four different energy types used (natural gas, fuel-oil, coal, and LPG)	Payback periods are 3.62, 2.28, 2.02 and 1.88 yr respectively.	(Balo, 2015)
Bio-char	Charcoal	Economic value	-	Economic value varies from \$9 t^{-1} (including only recalcitrant carbon) to \$15t^{-1} (including avoided emissions from energy production).	(Shackley et al., 2012a; Shackley et al., 2012b)

Based on the literature found, environmental, economic and social performances of some rice husk ash applications are reported. However, only some sustainability indicators are assessed for some rice husk ash applications. In addition, the sustainability performances of rice husk ash applications found from literature are not comparable since they are assessed using different indicators. Further comparison of sustainability characteristics of different rice husk ash applications using same indicators and units is essential.

Triple Bottom Line Assessment

To ease decision making, an attempt has been made to compare sustainability performances of different rice husk ash applications. Following the “triple bottom line” framework, all environmental, economic and social performances of the rice husk ash applications are needed to be taken into account. Several environmental, economic and social indicators are available. However, only main indicators such as reduction in greenhouse gas emissions, cost saving and employment generation are selected for consideration. These indicators are selected based on their significance and their data availability. Note that only rice husk ash use options where the ash is fully used in the process, and options having results for all indicators proposed are reported in this section.

Reduction in greenhouse gas emissions is sought by finding out how much greenhouse gas (GHG) emission can be reduced by replacing the conventional products by rice husk ash. Greenhouse gas emissions reduced is the amount of greenhouse gases released by using the conventional products. The amount of greenhouse gases released along the life cycle of products are sourced from the Thailand Greenhouse Gas Management Organization (2016) and Ecoinvent 2.2 database, analyzed by IPCC 2007 GWP 100a method. It is reported in the unit of kg CO_2 equivalent per tonne of conventional products.

Cost saving is the estimated cost that can be saved by replacing the conventional product by rice husk ash. Assuming that the ash is free of charge, this is just the price of the conventional products. Where standard prices are available, they are acquired from databases of the Bureau of Trade and Economic Indices (Bureau of Trade and Economic Indices, 2016a, b). For products that have no standard prices, current prices are sought by internet survey. It is reported in the unit of Thai baht (THB) per tonne of conventional product.

Employment generation is sought from Silalertruksa et al. (2012). This is reported in the unit of person-years employed per million Thai Baht spent in the economic sector. The sector identified is the industry using rice husk ash in their production processes. The economic sectors shown in Table 5 are selected from the list given in Silalertruksa et al. (2012). Estimated GHG reduction, cost saving and employment generation for each rice husk ash applications are presented in Table 5.

Table 5 Triple Bottom Line results of rice husk ash applications

Application	**Economic sector**	**Substituted product**	**GHG reduced (kg CO_{2eq}/t product)**	**Cost saved (THB/t product)**	**Employment generated (person-years/M THB)**
Concrete	Cement and concrete	Portland cement	760.0	2,694	1.57
Silica powders	Basic Industrial Chemicals	Commercial silica	22.30	1,000-4,000	2.04
Activated carbon	Basic Industrial Chemicals	Charcoal	1,005	5,000-8,000	2.04
Metal stabilization	Other Services & Unclassified	Portland cement	760.0	2,694	4.69
Soil conditioner	Paddy, Maize, Cereals	Lime	1,068	1,100-1,200	16
Brick	Other Services & Unclassified	Sand	3.700	292	4.69
Insulator	Iron and Steel products	Fire brick	241.0	4,700	1.14
Heat absorbing glass	Ceramic, Glass and Other non-metallic products	Sand	3.700	292	2.19
Rice mill wastewater treatment	Other Services & Unclassified	Charcoal	1,005	5,000-8,000	4.69
Bio-char	Other Services & Unclassified	Charcoal	1,005	5,000-8,000	4.69

THB = Thai Baht, the currency of Thailand; 1 THB is equal to approximately 0.029 US Dollar (at July 2016)

The results in Table 5 suggest that using rice husk ash to substitute for charcoal can help to reduce largest amount of greenhouse gases; and save the largest cost compared to other options. Using rice husk ash to replace charcoal in different sectors has a slightly different impact on employment generation. Using the ash in basic industrial chemical sector generates lower employment when compared to other services and unclassified sector. Based on review data in Table 5, it is suggested that using rice husk ash to substitute charcoal is the most sustainable option. However, there are also other important sustainability indicators to consider such as fossil fuel depletion, human toxicity, ecotoxicity, particulate matter formation, total net profit (TNP), total value added (TVA), and incomes of workers involved in production processes. Moreover, other factors such as rice husk ash properties, transportation of rice husk ash, infrastructure and technology for rice husk ash applications are also needed to be taken into consideration.

Conclusions

The sustainability characteristics of various rice husk ash utilization have been reviewed and reported. Many research papers, claiming sustainable/eco-friendly/environmental friendly/green applications of rice husk ash, report only technical performances of rice husk ash products. Only few papers also considered environmental and economic aspects of rice husk ash uses. Reporting on social issues of rice husk ash use was hardly found and thus should be considered for future studies.

In addition, this chapter compared sustainability performances of rice husk ash applications following “triple bottom line” framework. All environmental, economic and social indicators i.e. greenhouse gas emissions reduction, cost saving and employment generation were considered. It is suggested that using the ash to substitute for charcoal is the most sustainable option. However, other sustainable indicators such as fossil fuel depletion, human toxicity, ecotoxicity, particulate matter formation, total net profit (TNP), total value added (TVA), and incomes of workers should be considered in the future research. Moreover, further study on other factors such as rice husk ash properties, transportation of rice husk ash, infrastructure and technology for rice husk ash applications are also needed.

Chapter 3: Sustainability of utilization of rice husk ash from rice husk based power plants

Introduction

In this chapter, the current situation of rice husk ash left from the rice husk based powr plants are selected for assessing their sustainability characteristics. The sustainability indicators assessed include Climate change, Terestrial acidification, Freshwater eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Fossil depletion, total net profit (TNP) and total value added (TVA), employment generation and income of workers involved in production processes.

General context and selection of rice husk ash uses

Although chapter 2 reveals that there are several possibilities for rice husk ash uses, there are limitations for the uses of rice husk ash left from the rice husk based powe plants. This chapter will select actual uses of rice husk ash from the rice husk based power plants within the Thai context, to assses their environmental and socio-economic performances. From a survey conducted during June 2016, the rice husk ash utilization can be classified into two main groups, i.e. export and local uses. These will be discussed in the following sections.

Export

From interviews with persnonels from the rice husk based power plants, it was reported that rice husk ash having certain quality for clients are exported. Some interviewees reported that their rice husk ash is exported for use as insulator in steel industry. This kind of rice husk ash is in crystalline form and is in white color. Some interviewees did not identify how their ash is ued. Due to confidentiality, the contacts of rice husk ash export company were not provided from the rice husk based power plants. Therefore, the (exported) rice husk ash users by applications abd by regions are sought from literature. From the rice husk ash market study of Markets and Markets Private Limited (2017), it is seen that key rice husk ash users are in North America, Erope, Asia-Pacific, Middle East and Africa and South America.

Although the rice husk ash market study of Markets and Markets Private Limited (2017) reported that rice husk ash are used in building & construction, steel Industry, ceramics and refractory and rubber industries, it seems that in the Thai context, the export of rice husk ash are still limited to use in steel industry (from interviews with persnonels from the rice husk based power plants during June 2016). Interviewees from some rice husk based power plants claimed that their rice husk ash have quality to be used in cement and concrete industry, however, they currently face the problem of finding markets. It is expected that the market for Thai rice husk ash from rice husk based power plants will be expanded for more applications in the future. This means that larger amount of rice husk ash could be exported and could make more value added. However, the environmental impacts associated with its applications are needed to be studied.

Local uses

The rice husk ash not being exported (not having certain quality to export) are used locally. Local uses of rice husk ash from the rice husk based power plants can be classified into two main groups, i.e. gray rice husk ash and black rice husk ash. Gray color rice husk ash comes from both ash of rice husk solely (for the power plants using only rice husk as a fuel) and the ash of rice husk mixed with other fuels (for the power plants using rice husk and other bimass as fuels). This type of ash was reported to be used as soil conditioner in the rice fuel and is normally given away for free to the farmers. The black rice husk ash is the ash that is not burned completely. The main use of this type of ash is to use as one of ingredients in soil substrate production. In rare case it was reported by one of the rice husk based power plant participated in this project. Some of their rice husk ash is sold to be used as substituted fuel in brick industry. As rice husk ash is not fully burned, some energy content may remain and it can still be used as a fuel.

Selected rice husk ash uses to be studied

Export

Due to data unavailability from the survey conducted by the researcher, the selected rice husk ash uses for the exported ash are acquired from the rice husk ash market study of Markets and Markets Private Limited (2017). They reported that rice husk ash is used in building & construction, steel

Industry, ceramics and refractory and rubber industries. As described in chapter 2 that rice husk ash used in different applications require different forms of silica contained in the ash. A high concent of silica in rice husk ash is the significance of export for rice husk ash. To make it meaningful, the comparison of sustainability characteristics of rice husk ash uses will be done among the applications using same silica form contained in rice husk ash. The selected uses for exported rice husk ash and their contecxt are shown in Table 6. It is noted that the location of rice husk ash users in the analysis is assumed to be North America as it is reported as largest market for rice husk ash.

Table 6 The selected uses for exported rice husk ash and their contecxt

Application	Economic sector	Substituted product	Requirement
Concrete	Cement and concrete	Portland cement	Amorphous silica
Filler	Tyre and other rubber products	Commercial filler	Amorphous silica
Insulator	Iron and Steel products	Fire brick	Crystalline silica
Heat absorbing glass	Ceramic, Glass and Other non-metallic products	Quartz	Crystalline silica

Local uses

Based on the survey of this project, it is found that the rice husk ash not having certain quality (high silica content) is uses locally. To make it meaningful, the comparison of sustainability characteristics of rice husk ash uses will be done among the local applications using same quality of rice husk ash. Some local uses of rice husk ash do not seem to require high content of slilca. It seems to use other quality of the ash. For example, in soil substrate, the black rice husk ash is required for its nutrient, porousity and color. From an interview with the owner of one soil substrate, it was found that this industry requires only black rice husk ash as one of the ingredients, and there is no substutited product for the ash. Although, there may be some other munor uses of rice husk ash from rice husk based power plants, only main uses are examined in this study. The local uses of rice husk ash generated from rice husk based power plants, and their context are shown in Table 7.

Table 7 The selected local rice husk ash uses and their contecxt

Application	Economic sector	Substituted product	Requirement
Soil conditioner	Paddy, Maize, Cereals	Lime	Not specific, can be both black and gray rice husk ash
Soil substrate	Other Services & Unclassified	-	Black rice husk ash

Environmental performance

The environmental impacts of rice husk ash uses include impacts of transportation of rice husk ash and avoided environmental impacts of substituted products. The rice husk ash generated in the rice husk based power plant is consifered waste. Therefore, its environmental impacts are not accounted for. The environmental impacts are assessed based on processing 1,000 tonnes of rice husk ash in all selected uses to study.

Export

For export option, the environmental impacts of rice husk ash uses include impacts of transportation of rice husk ash (both domestic and international) and avoided environmental impacts of substituted products. For domestic trasnsportation, it is assume using truck with distance of 500 km. For international transport, it is assumed to be shipping with closet distance between commercial ports of Thailand and USA. The characterized environmental impacts associated with exporting 1,000 tonnes of rice husk ash in the selected rice husk ash uses are presented in the following sections.

Amorphous silica uses

1) <u>Concrete in construction industry</u>

The characterized environmental impacts of using exported 1,000 t of rice husk ash in construction industry in the US are shown below. In construction industry, the rice husk ash is used to substitute Portland cement.

Table 8 Characterized environmental impacts of exporting 1,000 t of rice husk ash for use in construction industry

Impact category	Unit	Total
Climate change	kg CO2 eq	-1.19E+06
Human toxicity	kg 1,4-DB eq	-7.00E+04
Particulate matter formation	kg PM10 eq	-1.10E+03
Terrestrial acidification	kg SO2 eq	-2.98E+03
Freshwater eutrophication	kg P eq	2.48E+00
Marine eutrophication	kg N eq	-3.95E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	-5.67E+00
Freshwater ecotoxicity	kg 1,4-DB eq	2.30E+01
Marine ecotoxicity	kg 1,4-DB eq	3.32E+02
Fossil depletion	kg oil eq	-6.33E+04

Analyzed by ReCiPe Midpoint V1.04 method

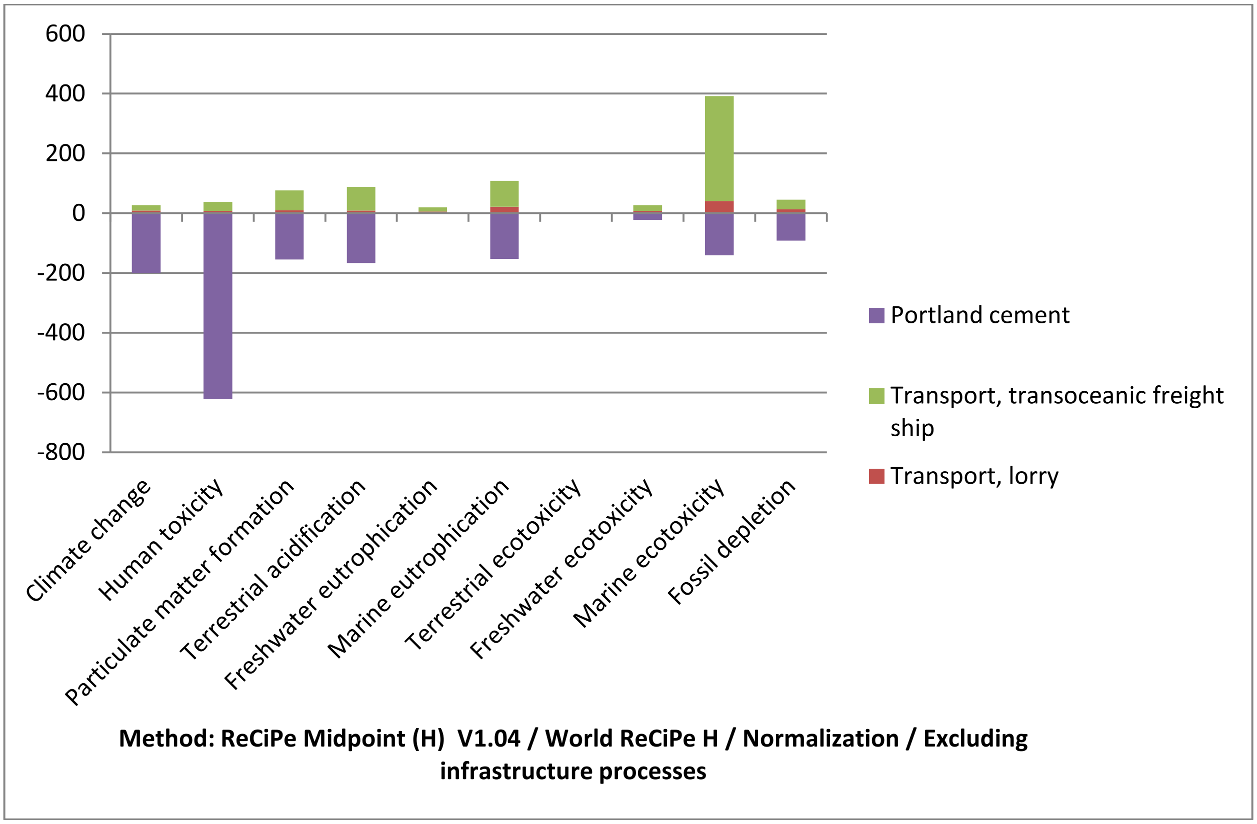

Figure 6 Normalized environmental impacts of exporting 1,000 t of rice husk ash for use in construction industry

The negative impacts shown are the environmental benefits gain by substituting Portland cement by rice husk ash. Normalized impacts show magnitudes of all impact categories in same unit (person-year), therefore, they are comparable. The results in Figure 6 suggest that using rice husk ash in the US contruction industry can help to reduce human toxicity in largest extent, followed by climate change, marine eutrophication, terrestrial acidification, marine ecotoxicity, particulate matter formation and fossil depletion repectively. The main contributing process is coal production. In US cement production require large amount of coal. While, positive environmental impacts caused by using exported rice husk ash is mainly marine ecotoxicity, contributed by marine shipping.

2) Filler in rubber industry

The characterized environmental impacts of using exported 1,000 t of rice husk ash in rubber industry in the US are shown below. In rubber industry, the rice husk ash is used to substitute commercial filler. In this study the commercial filler used in the analysis is acrylic filler.

Table 9 Characterized environmental impacts of exporting 1,000 t of rice husk ash for use in rubber industry

Impact category	Unit	Total
Climate change	kg CO2 eq	-2.12E+05
Human toxicity	kg 1,4-DB eq	-7.71E+04
Particulate matter formation	kg PM10 eq	5.06E+02
Terrestrial acidification	kg SO2 eq	1.74E+03
Freshwater eutrophication	kg P eq	-1.02E+02
Marine eutrophication	kg N eq	6.45E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	-2.55E+01
Freshwater ecotoxicity	kg 1,4-DB eq	-1.76E+03
Marine ecotoxicity	kg 1,4-DB eq	-1.38E+03
Fossil depletion	kg oil eq	-1.61E+05

Analyzed by ReCiPe Midpoint V1.04 method

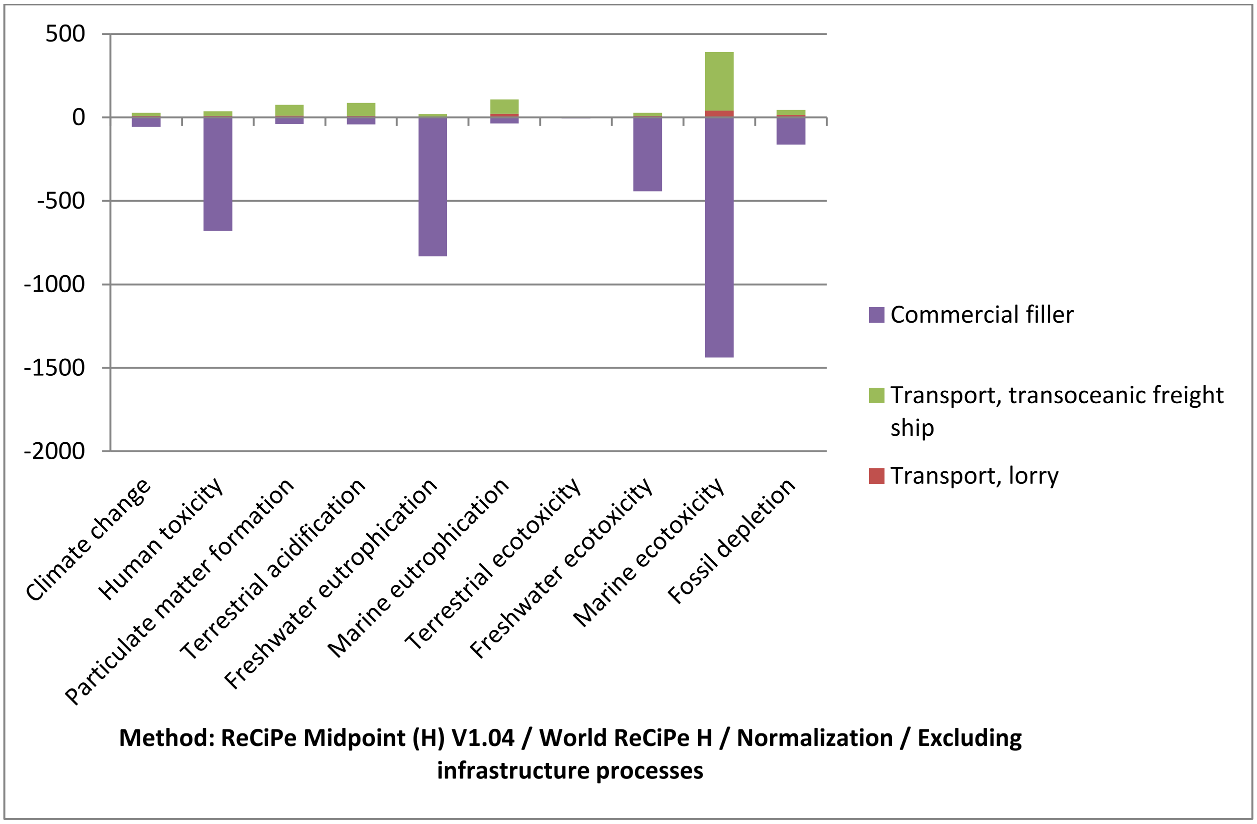

Figure 7 Normalized environmental impacts of exporting 1,000 t of rice husk ash for use in rubber industry

The results in Figure 7 suggest that using rice husk ash in the US rubber industry can help to reduce marine ecotoxicity in largest extent, followed by freshwater eutrophication, human toxicity, freshwater ecotoxicity, fossil depletion and climate change repectively. The main contributing process is acrylic binder production which consumes electricity intensively, and process of titanium dioxide used in the acrylic filler production. Silimar to other export options, positive environmental impacts caused by using exported rice husk ash is mainly marine ecotoxicity, contributed by marine shipping.

Crystalline silica uses

1) <u>Insulator in steel industry</u>

The characterized environmental impacts of using exported 1,000 t of rice husk ash in steel industry in the US are shown below. In steel industry, the rice husk ash is used to substitute fire brick.

Table 10 Characterized environmental impacts of exporting 1,000 t of rice husk ash for use in steel industry

Impact category	Unit	Total
Climate change	kg CO2 eq	-9.77E+05
Human toxicity	kg 1,4-DB eq	-1.44E+05
Particulate matter formation	kg PM10 eq	1.04E+01
Terrestrial acidification	kg SO2 eq	9.01E+02
Freshwater eutrophication	kg P eq	-2.33E+02
Marine eutrophication	kg N eq	-2.30E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	-5.51E+00
Freshwater ecotoxicity	kg 1,4-DB eq	-3.21E+03
Marine ecotoxicity	kg 1,4-DB eq	-2.71E+03
Fossil depletion	kg oil eq	-3.75E+05

Analyzed by ReCiPe Midpoint V1.04 method

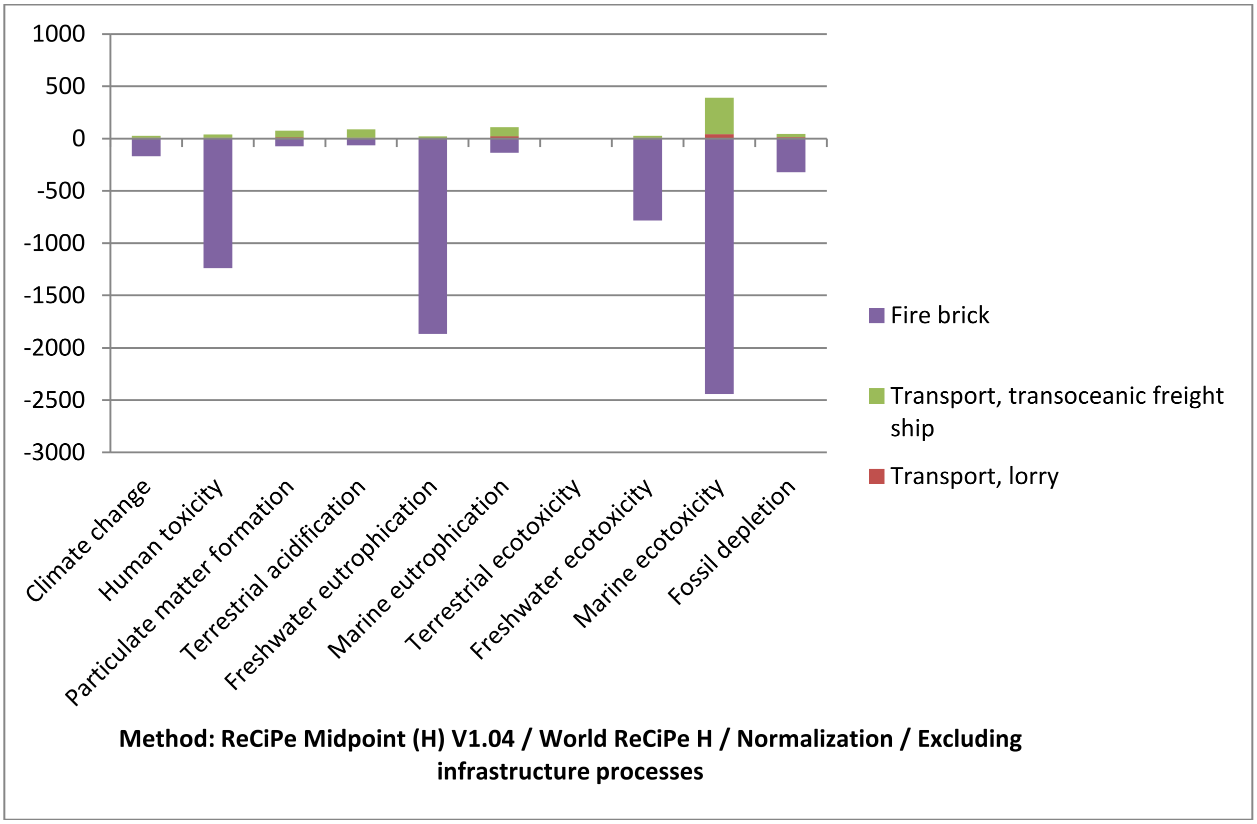

Figure 8 Normalized environmental impacts of exporting 1,000 t of rice husk ash for use in steel industry

The results in Figure 8 suggest that using rice husk ash in the US steel industry can help to reduce marine ecotoxicity in largest extent, followed by freshwater eutrophication, human toxicity, freshwater ecotoxicity, fossil depletion and climate change repectively. The main contributing process is the production of fire brick itself which use great amount of electricity. Whereas, positive environmental impacts caused by using exported rice husk ash is mainly marine ecotoxicity, contributed by marine shipping.

2) <u>Quartz in ceramics industry</u>

The characterized environmental impacts of using exported 1,000 t of rice husk ash in ceramics industry in the US are shown below. In ceramics industry, the rice husk ash is used to substitute Quartz.

Table 11 Characterized environmental impacts of exporting 1,000 t of rice husk ash for use in ceramics industry

Impact category	Unit	Total
Climate change	kg CO2 eq	1.77E+05
Human toxicity	kg 1,4-DB eq	4.18E+03
Particulate matter formation	kg PM10 eq	1.05E+03
Terrestrial acidification	kg SO2 eq	3.31E+03
Freshwater eutrophication	kg P eq	2.15E+00
Marine eutrophication	kg N eq	9.62E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	9.58E+00
Freshwater ecotoxicity	kg 1,4-DB eq	1.10E+02
Marine ecotoxicity	kg 1,4-DB eq	5.12E+02
Fossil depletion	kg oil eq	6.12E+04

Analyzed by ReCiPe Midpoint V1.04 method

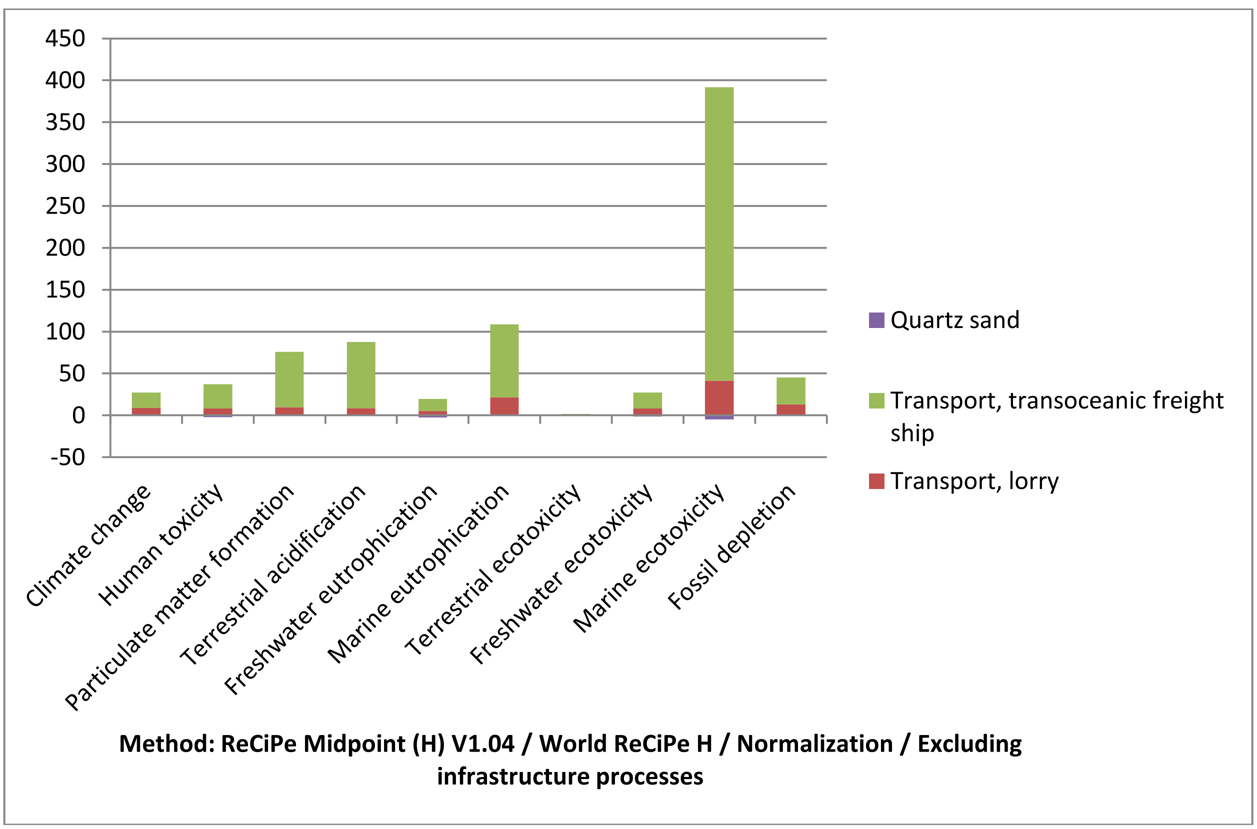

Figure 9 Normalized environmental impacts of exporting 1,000 t of rice husk ash for use in ceramics industry

The results in Figure 9 suggest that using rice husk ash in the US ceramics industry can help to reduce little impacts compared the the positive impacts in marine ecotoxicity contributed by marine shipping. This is because the environmental impacts of quartz are considered a lot less than that of the shipping.

Local uses

The environmental impacts associated with using 1,000 tonnes of rice husk ash in the selected rice husk ash uses are presented in the following sections.

Black rice husk ash

Ingredient in soil substrate industry

The characterized environmental impacts of using 1,000 t of rice husk ash in soil substrate industry are shown below. In soil substrate, the rice husk ash is used as one of main ingredients. Therefore, there is no substituting product in this option.

Table 12 Characterized environmental impacts of local use of 1,000 t of rice husk ash in soil substrate industry

Impact category	Unit	Total
Climate change	kg CO2 eq	5.29E+03
Human toxicity	kg 1,4-DB eq	9.58E+01
Particulate matter formation	kg PM10 eq	1.36E+01
Terrestrial acidification	kg SO2 eq	3.19E+01
Freshwater eutrophication	kg P eq	6.51E-02
Marine eutrophication	kg N eq	1.92E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	5.98E-01
Freshwater ecotoxicity	kg 1,4-DB eq	3.40E+00
Marine ecotoxicity	kg 1,4-DB eq	5.46E+00

Fossil depletion	kg oil eq	1.79E+03

Analyzed by ReCiPe Midpoint V1.04 method

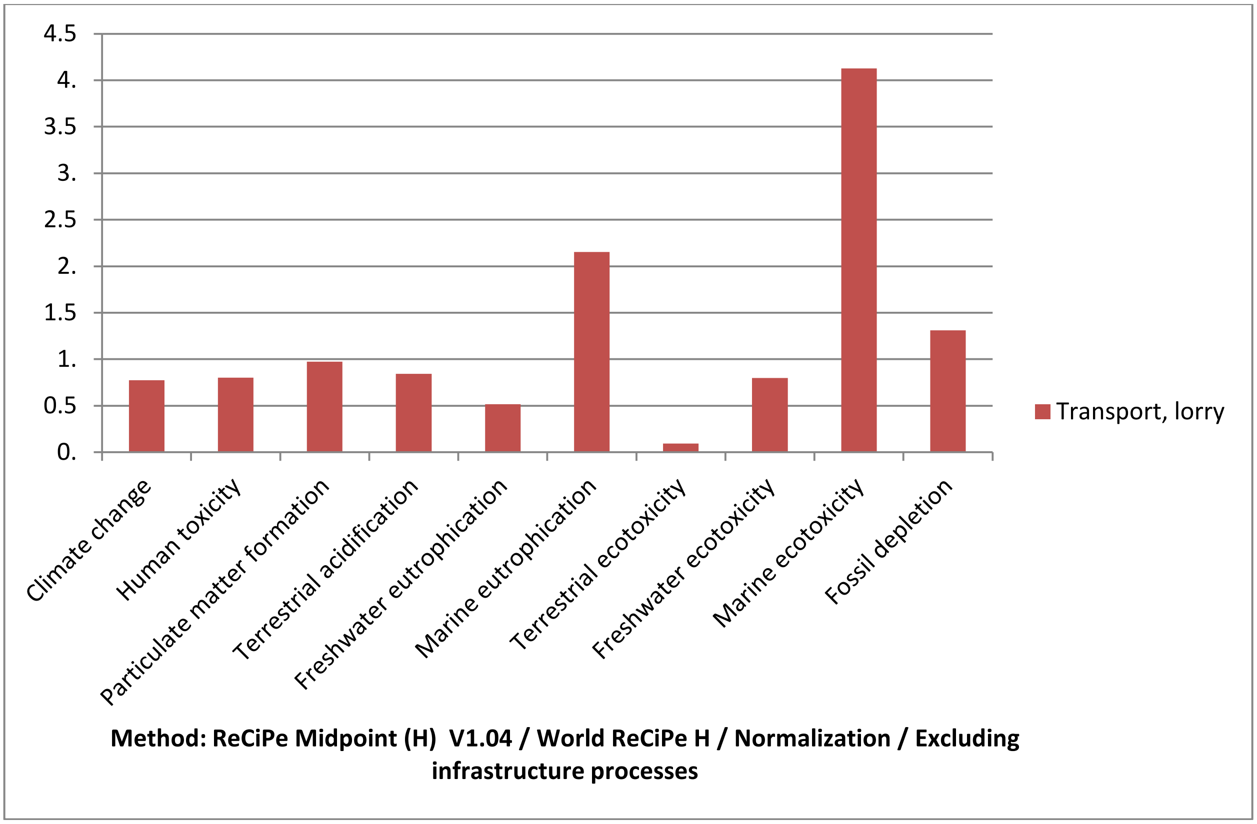

Figure 10 Normalized environmental impacts of local use of 1,000 t of rice husk ash in soil substrate industry

As rice husk ash is not substituting for other product in this industry, there are only positive impacts from local transport by truck shown in Figure 10. This means that using rice husk ash in this option could not help to reduce environmental impacts. Yet, it may have socio-econmic benefits, which is to be discussed in the next section.

Gray and black rice husk ash

<u>Soil conditioner</u>

The characterized environmental impacts of using 1,000 t of rice husk ash as soil conditioner are shown below. In this option, the rice husk ash is used to substitute for lime.

Table 13 Characterized environmental impacts of local use of 1,000 t of rice husk ash as soil conditioner

Impact category	Unit	Total
Climate change	kg CO2 eq	-7.90E+05
Human toxicity	kg 1,4-DB eq	-3.65E+03
Particulate matter formation	kg PM10 eq	-2.91E+02
Terrestrial acidification	kg SO2 eq	-6.20E+02
Freshwater eutrophication	kg P eq	-3.04E+00
Marine eutrophication	kg N eq	-1.90E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	-1.65E+00
Freshwater ecotoxicity	kg 1,4-DB eq	-1.48E+02
Marine ecotoxicity	kg 1,4-DB eq	-7.45E+01
Fossil depletion	kg oil eq	-8.73E+04

Analyzed by ReCiPe Midpoint V1.04 method

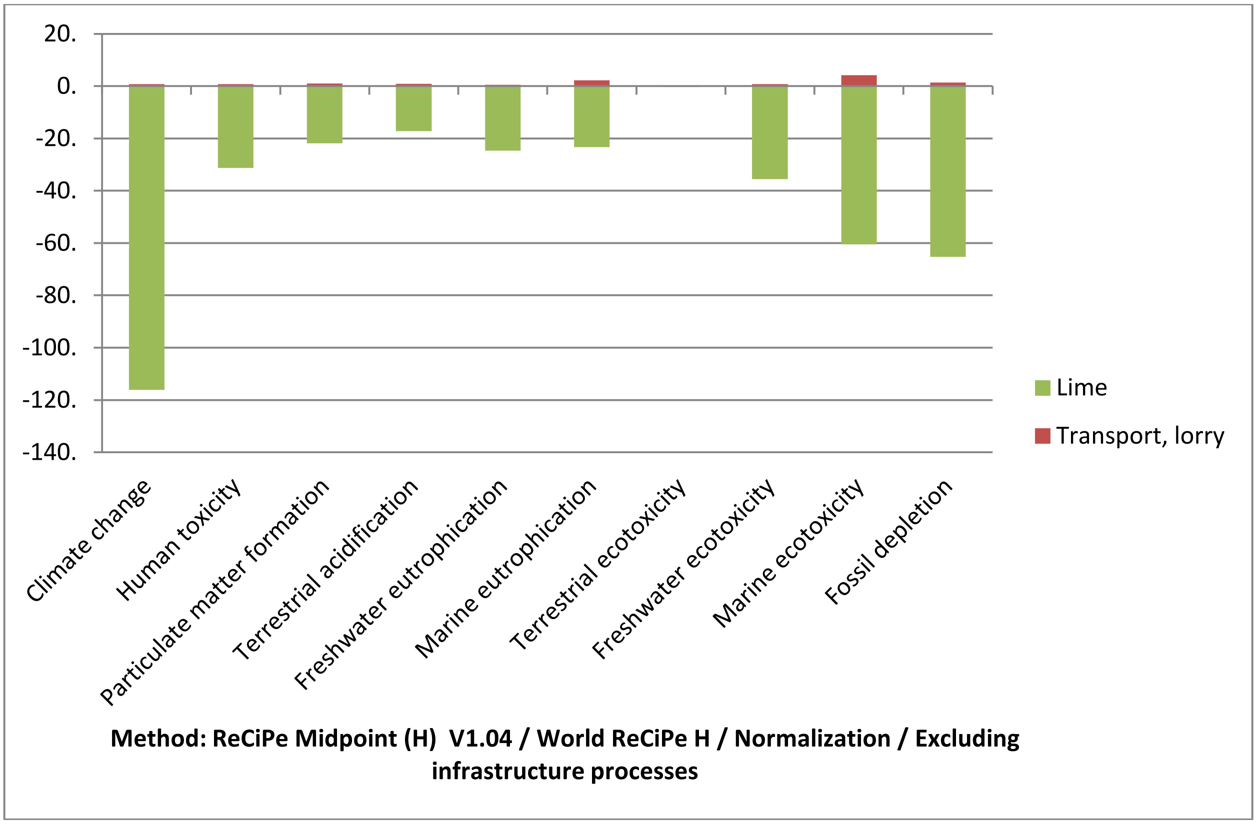

Figure 11 Normalized environmental impacts of local use of 1,000 t of rice husk ash as soil conditioner

The results in Figure 11 suggest that using rice husk ash as soil conditioner can help to reduce climate change in largest extent, followed by fossil depletion, marine ecotoxicity, freshwater ecotoxicity, human toxicity, freshwater and marine, particulate matter formation and terrestrial acidification repectively. The main contributing process is the production of lime which emits large amount of CO_2. Whereas, positive environmental impacts caused by using rice husk ash in this option is mainly contributed by transport by truck.

Socio-economic performance

Export

The socio-economic performace of exporting rice husk ash in this study refers to the socio-economic benefits gain within Thailand. This is because of the confidentiality; the rice husk power plants did not provide contact of rice husk ash export compay. Therefore, locations and applications and substituted products of rice husk ash could not be indentified. Thus, costs associated with handling and use of rice husk ash in foreign country could not be tracked down.

The socio-economic performace includes the total net profit (TNP), total value added (TVA), employment generation and worker income in sectors involved. TNP includes profits from selling rice husk ash gain by the rice husk based power plants. TVA includes TNP from selling rice husk ash plus personnel remuneration in domestic transportation sector. Note that taxes from selling rice husk ash and transportation are excluded as they are excepted by law. In addition, profit from transportation of rice husk ash is not included as data is not available.

For exporting rice husk ash, the total net profit (TNP), total value added (TVA), employment generation and worker income in sectors involved are assessed using information from literarure as direct contact with the transportation contractors could not be made. In addition, there is no cost of exporting rice husk ash (for the rice husk based power plants), therefore, total net profit (TNP) is equal to selling price of the ash. Socio-economic performances of exporting rice husk ash are shown in Table 8. Note that the socio-economic performances of exporting the ash is similar for all applications as socio-economic performances in this study refers to the benefits gain by rice husk ash power plants and the transportation contractors.

Table 14 Economic performance of export of rice husk ash

Total net profit (THB/1,000 t of rice husk ash)	**Total value added (THB/1,000 t of rice husk ash)**	**Employment generation[1] (person-years/ M THB)**	**Employment generation[2] (person-years/1,000 t of rice husk ash)**	**Worker income[3] (THB/1,000 t of rice husk ash)**
4,650	2.79E5	2.09	1.34	2.74E5

THB = Thai Baht, the currency of Thailand; 1 THB is equal to approximately 0.031 US Dollar (at April 2018)

[1] from (Silalertruksa et al., 2012)

[2] estimated using data from (Silalertruksa et al., 2012) and value of final product gain from processing 1,000 t of rice husk ash into the processes

[3] calculated using wage data from (Bank of Thailand, 2018) and transportation cost from Comptroller General's Department, assuming distance of 500 km

Local uses

The socio-economic performaces of local uses for rice husk ash includes the total net profit (TNP), total value added (TVA), employment generation and worker income in sectors involved. TNP includes profits from selling rice husk ash gain by the rice husk based power plants, plus cost saved by replacing conventional products by rice husk ash, deducted by cost of transportation of rice husk ash (profit for rice husk ash users). It should be noted that for local rice husk ash uses, the users are responsible for rice husk ash transportation. Therefore, the cost of transportation is included in their production cost. TVA includes TNP from selling rice husk ash and profit of rice husk ash users (by replacing conventional products by rice husk ash) plus personnel remuneration in sectors using rice husk ash. Note that taxes from selling rice husk ash and transportation are excluded as they are excepted by law. Socio-economic performances of local uses of rice husk ash are shown in Table 9.

Table 15 Economic performance of local uses of rice husk ash

Application	**Economic sector**	**Substituted product**	**Total net profit (THB/1,000 t of rice husk ash)**	**Total value added (THB/1,000 t of rice husk ash)**	**Employment generated[1] (person-years/M THB)**	**Employment generation[2] (person-years/1,000 t of rice husk ash)**	**Worker income[3] (THB/1,000 t of rice husk ash)**
Soil conditioner	Paddy, Maize, Cereals	Lime	9.5E5	1.15E6	16	128	1.35E7
Soil substrate	Other Services & Unclassified	-	-	2E5	4.69	46.9	3.38E6

[1] from (Silalertruksa et al., 2012)

[2] estimated using data from (Silalertruksa et al., 2012) and value of final product gain from processing 1,000 t of rice husk ash into the processes

[3] calculated using wage data from (Bank of Thailand, 2018)

Concluding remarks

This chapter has reported the results of environmenal and socio-economic performances of selected rice husk ash use options, both export and local uses. The sustainability indicators assessed include Climate change, Terestrial acidification, Freshwater eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Fossil depletion, total net profit (TNP) and total value added (TVA), employment generation and income of workers involved in production processes. The results in this chapter will be used to discuss in the next chapter to make conclusions for this project and to provide recommendations for policy makers.

Chapter 4: Conclusions and recommendations

Conclusions

This chapter provides conclusions for environmental and socio-economic performances of selected rice husk ash use alternatives, using results from chapters 3. In addition, it provides recommendations to help manage rice husk ash utilization in a more sustainable way.

Environmental aspect

Export

For amorphous silica rice husk ash, using it in rubber indsutry is more environmentally friendly than using it in construction industry. This is because when using it in rubber industry, it is used to substitute for commercial filler. The commercial filler generates more impacts than Portland cement. However, using to replace porland cement can also help to reduce great environmental impacts.

For crystalline silica rice husk ash, using it in steel industry is better in terms of environmental aspect. This is because when using it in steel industry, the ash is used to replace fire brick which consumes electricity intensively. Its production process thus create great environmental impacts. While, using the ash in ceramics industry, it is used to replace Quartz, which generates impacts less than that of fire brick. However, it is to note that crystalline silica is considered harmful for human health (Bronzeoak Ltd., 2003). Therefore, the market for this type of rice husk ash may be limited in the future.

Local

The results show that using rice husk ash as soil conditioner is more environmentally friendly than using it as one main ingredients in soil substrate industry. This is because when using the ash as soil conditioner, it is used to substitute for lime. Production of lime causes great impacts. Whereas, using it in soil substrate does not gain environmental benefits because the ash is not used to substitute for other product.

Socio-economic aspect

<u>Export</u>

Based on boundary of this study, all rice husk ash uses for export option have same socio-economic benefits. These include total net profit (TNP) and total value added (TVA), employment generation and income of workers involved in production processes of the rice husk based power plants and domestic transportation sector.

<u>Local</u>

For local uses of rice husk ash, the use of rice husk ash as soil conditioner seems to have better socio-economic benefits. However, the use of rice husk ash in soil substrate industry can also provide great socio-economic benefits. More importantly, it is to note that this industry relies significant on the rice husk ash from the rice husk based power plants. This is because the black rice husk ash is required as one of the main feedstocks in the soil substrate industry.

Limitations and opportunities

The main feature of rice husk ash for use in several applications (required for export) is its high silica content. This can be a problem when rice husk is mixed with other biomass fuels, as the export company requires rice husk ash from using rice husk as a sole fuel in the power plants. Moreover, from the survey of this project, it was found that some rice husk based power plants having high quality of rice husk ash still can not find markets to export. In addition, some rice husk based power plants still keep their ash to find better ways to deal within.

Recommendations

1. Assistance to find markets for rice husk based power plants should be provided to help them find better ways to deal with the ash. This way will help manage the ash more sustainable.
2. The use of amorphous rice husk ash in rubber and construction industries should also be promoted in Thailand.

3. Black rice husk ash from the rice husk based power plants should be given priority for use in soil substrate industry as this industry relies on the rice husk based power plants only for this type of ash.

4. The rice husk based power plants with potential in terms of technology and feedstock should be promoted to use rice husk solely as a fuel. This is to produce high quality ash for export.

5. The rice husk ash not having high quality for export and are left in the power plants, may be used as soil conditioner. This option can provide both environmental and socio-economic benefits.

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Sustainable utilization of rice husk ash from power plants: A review

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To move towards sustainability, finding sustainable ways of using rice husk ash for a large rice producing country like Thailand is essential. This review seeks to find sustainability characteristics of the uses of rice husk ash from power plants. It also reviews how rice husk ash is produced from different power generation technologies. Characteristics of rice husk ash are affected by different factors such as sources, preparation methods and combustion technologies. Different forms of rice husk ash, amorphous and crystalline, suit different applications. Ash from moving grate technology is suggested for use as adsorbent while that from fluidized bed is suggested for use as filler in polymeric composites and in the synthesis of innovative ceramic compounds. The ash from suspension fired technology is suggested for use in the construction industry and zeolite production. In addition to technical viability, using rice husk ash to substitute conventional products helps gain both environmental and economic benefits. Despite claiming sustainable applications of rice husk ash, many research papers report only technical performances of the products. This paper draws out sustainability characteristics of different rice husk ash applications using the “triple bottom line” framework. Potential reduction of greenhouse gas emissions, cost saving and employment generation of rice husk ash use options have been investigated. Results from the review suggest that using the ash to replace charcoal is the most sustainable option when comparing with other alternatives such as Portland cement, commercial silica and lime. This option could help to reduce GHG up to 1005 kg CO_{2eq}/t product, to save cost up to 8000 THB/t product, as well as to help generate employment for about 5 person-years/M THB spent in the sector. However, to make the sustainability assessment more comprehensive, other sustainability indicators such as fossil fuel depletion, human toxicity, ecotoxicity, particulate matter formation, total net profit (TNP), total value added (TVA), and incomes of workers are also needed to be considered in future research.

1. Introduction

Sustainable development is an important matter worldwide and Thailand is also focusing on the sustainability issue in different sectors as appearing also in its sustainable development goals (United Nations, 2015). To help achieve sustainability, the “triple bottom line” is often used. This framework promotes taking into consideration all environmental, economic and social aspects (Elkington, 2002). To avoid looking at a single dimension of sustainability in isolation like many conventional sustainability assessments, this framework was developed to assess multiple dimensions of sustainability, i.e. environment, economy and society. This framework is useful for decision makers to identify consequences of activities' impacts on all environmental, economic and social dimensions. This would provide supporting information to help policy makers in choosing actions that lead to a sustainable society.

Biomass energy is the most important alternative energy source for Thailand. As an agricultural based economy, Thailand has abundant biomass resources. Biomass is considered relatively clean compared with fossil fuels (Sajjakulnukit et al., 2005). Accordingly, the Thai government has promoted the use of biomass for energy purposes to substitute fossil fuels, in order to help conserve nonrenewable resources and reduce environmental impacts (Amornkosit, 2007; Coovattanachai, 2006; Lertsuridej, 2004). The largest source of biomass in Thailand is agricultural residues, i.e.

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bagasse, rice husk, palm oil wastes, and wood residues (Sajjakulnukit et al., 2005).

Rice is the most important agricultural product of Thailand. It is both staple food for Thailand's population and the main export product of the country. Thailand produces a large amount of rice. In 2014, Thailand produced about 38 million tonnes of rice (Office of Agricultural Economics, 2014). Rice husk is a co-product of rice products generated in the rice milling process, accounting for about 23 percent of the total paddy weight (rice crop weight) (Prasertsan and Sajjakulnukit, 2006). The husk has sometimes been used as an energy source in the rice mills themselves. Rice husk is considered one of the major biomass feedstocks in Thailand as it has a large available amount and is conveniently collectable from the mills (Sajjakulnukit et al., 2005).

Most rice husk in Thailand is currently being used to produce electricity on a commercial scale. This is indicated by increased numbers in rice husk fuelled power plants registered (Energy Policy and Planning Office, 1999; 2014). Based on production capacities of the rice husk fuelled power plants registered, more than 6 million tonnes of rice husk (which accounts for nearly 70 percent of the total rice husk generated annually) is being used to produce electricity (Energy Regulatory Commission, 2015).

Rice husk is used as a fuel in the boiler to generate steam for generator turbine to provide electricity. Rice husk ash is a waste generated when burning rice husk in a boiler. There are several potential uses of rice husk ash from power plants as reviewed in Pode (2016) and Kumar et al. (2013). However, those previous reviews only deal with possibilities of using rice husk ash in different applications with regards to technical viability. The sustainability aspects of the rice husk ash uses have not yet been investigated.

Proper management of rice husk ash from rice husk based power plants is essential. To help promote sustainable development, there is a need to find sustainable ways of using this ash. This review extracts sustainability performances of different rice husk ash applications in environmental, economic and social aspects. In addition, it identifies gaps for future research. This paper provides useful information for policy makers involved in rice husk based power plant sector.

2. Methods

2.1. Literature search

The Scopus database was used to support the literature search for this review. Major well-known bibliometric information sources are the Web of Science, Scopus and Google Scholar. Among these, Scopus is the largest source offering citation abstract and database of peer-reviewed literature. Scopus includes scientific journal articles, books and papers from conference proceedings. Moreover, a study of Gavel and Iselid (2008) revealed that there is a large match between the citation search results from the Web of Science and Scopus databases.

2.2. Screening process

There are several keywords used to search for literature. The authors first used the keyword "rice husk ash", the results came out with 1808 references published from 1977 to 2016 from several areas of study. The authors then attempted to narrow down the search results using different keywords: rice husk ash/sustainable/sustainability/green product/eco-friendly/environmental friendly/environmental/economic/socio-economic/social.

2.3. Selection of literature

The abstracts of all references found from the screening process were read to see if those studies were related to sustainability assessment of rice husk ash uses. The full-texts of the references found to be relevant were accessed using available online databases. The references selected for review were those with the terms used in the screening process; the terms being included either in the article title, abstract or keywords of the references. Final selection of literature consisted of 21 references which were then used to review the sustainability characteristics of rice husk ash applications.

2.4. Sustainability assessment of rice husk ash applications from literature

Following the "triple bottom line" framework, all the selected references were read in detail to extract results on environmental, economic and social aspects of the rice husk ash applications. To ease comparison of sustainability performances across different rice husk ash use options, attempt was made to find results on same indicators and units for different options. In case the results found from the selected references were not in the same units, extra analyses on environmental, economic and social aspects of the rice husk ash applications were conducted by the authors. This is to have results for same indicators and same units which will allow the comparison of sustainability performances of different rice husk ash use options leading to useful recommendation.

3. Rice husk ash and its uses

This section describes how rice husk ash is generated in the power production. Different technologies for converting rice husk to electricity are discussed. Moreover, it describes rice husk ash characteristics and potential applications of the ash classified by types of rice husk ash.

3.1. Power and rice husk ash generation

At present, combustion is the most commonly used technology for rice husk fuelled power generation. However, other potential technologies such as gasification and pyrolysis are also available. Therefore, the main current and potential technologies, i.e. combustion, gasification and pyrolysis were selected to discuss in this paper.

3.1.1. Combustion

Combustion is a thermochemical process that converts fuel into a hot flue gas which is then used in steam turbines or steam engines to produce heat, steam or electricity (Dinkelbach, 2000). Combustion technology is well established and several Thai rice husk based power plants use it in their production (Energy Policy and Planning Office, 2011).

Rice husk is used as a fuel in the boiler furnace of a power plant. There are three main boiler types used in rice husk fuelled power plants; i.e. stoker, suspension fired and fluidized bed boilers. The stoker boiler is the most common type used among the Thai biomass power plants (Witchakorn and Bundit, 2004). Rice husk is burned differently in different types of boiler furnaces. In stoker boiler furnaces, rice husk is rested on a grate and burned while moving through the furnace. In a suspension fired boiler, the husk is ground before being ejected to burn in the combustion chamber. In the fluidized bed system, the husk is burned in a turbulent bed of hot inert material (Bridgwater et al., 2002).

In general, the rice husk fuelled power plant consists of water pre-treatment, boiler and electricity generator units. For those using suspension fired boilers, a rice husk grinder unit is also installed. Rice husk is burned in the furnace to produce hot flue gas which is then used to heat up pre-treated water in the boiler to generate steam. The high pressure and temperature steam drives the blades of the steam turbine that are connected to an electricity generator. Some of the electricity generated is used internally in the plant and the surplus is transmitted to the grid. The excessive steam released from the turbine is then condensed into water, which is recycled in the boiler (Chungsangunsit et al., 2010). The process diagram for rice husk fuelled power generation using combustion system is shown in Fig. 1.

Rice husk fuelled power plants release two forms of the rice husk ash, bottom ash and fly ash, which are collected separately. The bottom ash is collected at the base of the furnace whereas the fly ash is captured by the air treatment system. In most cases, the rice husk ash can be easily collected except in the fluidized bed furnace, where the bottom ash is mixed with the bed material when removed (Thepnoo, 2006). The emissions generated from rice husk combustion in a furnace can be vary slightly with the furnace burning technologies. Emissions and waste generated from rice husk fuelled power production using stoker and suspension fired boilers are shown in Table 1.

From Table 1, it is seen that CO_2 is the main emission released from rice husk combustion. The differences in quantities of emissions and ash for these two boiler technologies may be caused by different factors, for example, the amount of rice husk consumed, furnace combustion efficiencies and chemical compositions of rice husk. The CO emission from the suspension-fired boiler furnace is lower than that of the stoker one. This may be due to the higher combustion efficiency of the former where rice husk is ground before being air-injected into the furnace. This could help increase the rice husk surface area for combustion, thus increasing combustion efficiency and consequently reducing the amount of rice husk required in the furnace.

3.1.2. *Gasification*

Gasification is a thermochemical process that converts fuel into a combustible gas. In the gasification process, partial oxygen is supplied to yield the combustible gas or producer gas. The producer gas contains combustible components such as carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). This gas can be used as a fuel in boilers, engines or gas turbines. The advantage of gasification is that the producer gas can be used in prime movers (gas engines, gas turbines, fuel cells) to generate electricity at higher efficiency (Dinkelbach, 2000).

In Thailand, gasification technology for power production from biomass exists. However, it is less widely used in rice husk based power plants as compared to direct combustion. At present, there are few small rice husk based power plants using gasification technology, with power capacities ranging between 20 and 400 kWe. However, they are still in the demonstration stage (Assanee and Boonwan, 2011).

In general, gasification system consists of feed storage, feed drying, gasifier, gas treatment and generator equipment. The rice husk gasification plants in Thailand use gas engines and modified diesel engines to generate electricity. In modified diesel engine, both diesel and producer gas are used to run the generator (Assanee and Boonwan, 2011). There are different configurations of biomass gasifiers. The major configurations are downdraft, updraft, bubbling and circulating fluidized beds. Yet, only the fluidized bed configurations have generating capacities of over 1 MWe (Bridgwater et al., 2002). Process diagram for rice husk fuelled power generation using gasification system is presented in Fig. 2.

An ideal gasification process yields only non-condensable gas (producer gas) and ash residue. However, the gas produced from incomplete gasification is also contaminated with particulates, tars, alkali metals and fuel-bound nitrogen compounds. The ash residue also contains some char (Bridgwater et al., 2002). If water is used in the gas treatment process, waste water is also generated.

3.1.3. *Pyrolysis*

Pyrolysis is the thermal degradation of biomass in an absence of oxygen. Pyrolysis of biomass produces gas, char and vapour which can be collected as a liquid. This liquid (pyrolysis oil) is a mixture of oil, tar and water (Bridgwater et al., 2002; Dinkelbach, 2000). The amounts and proportion of pyrolysis products generated depend on temperature, heating rate and residence time. Pyrolysis is classified into slow, fast and flash pyrolysis, based on the differences in the above-mentioned factors (Dinkelbach, 2000).

Slow pyrolysis uses lower heating rate, longer residence time and lower temperature. The main product from slow pyrolysis is char; some smaller amounts of oil and gas are also produced when higher temperatures and shorter residence times are used. Fast pyrolysis is developed to yield more oil so the main product produced from fast pyrolysis is pyrolysis oil. Flash pyrolysis is conducted at very high heating rate and temperature, and very short residence time. The main product of flash pyrolysis is gas

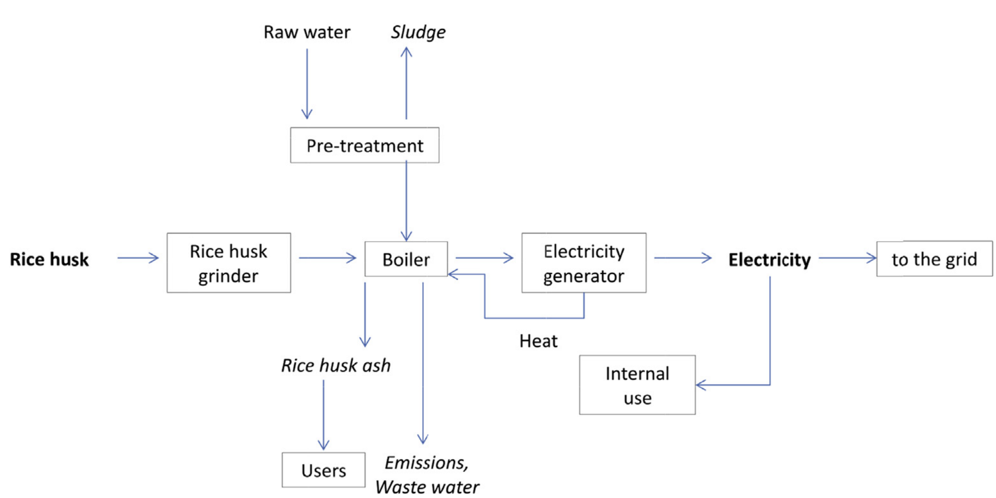

Fig. 1. Process diagram for rice husk fuelled power generation using combustion system.

Table 1
Emissions and waste generated from rice husk fuelled power plants using combustion systems.

Parameters	Unit	Stoker boiler[a]	Suspension-fired boiler[b]
Carbon dioxide (CO_2)	kg/MWh	1690	1480
Carbon monoxide (CO)	kg/MWh	8.58	1.65
Nitrogen dioxide (NO_2)	kg/MWh	1.31	2.02
Sulfur dioxide (SO_2)	kg/MWh	0.39	1.23
Total Suspended Particulates (TSP)	kg/MWh	0.11	0.67
Rice husk ash	kg/MWh	198	193

Source.
[a] Chungsangunsit et al. (2010).
[b] Prasara-A (2010).

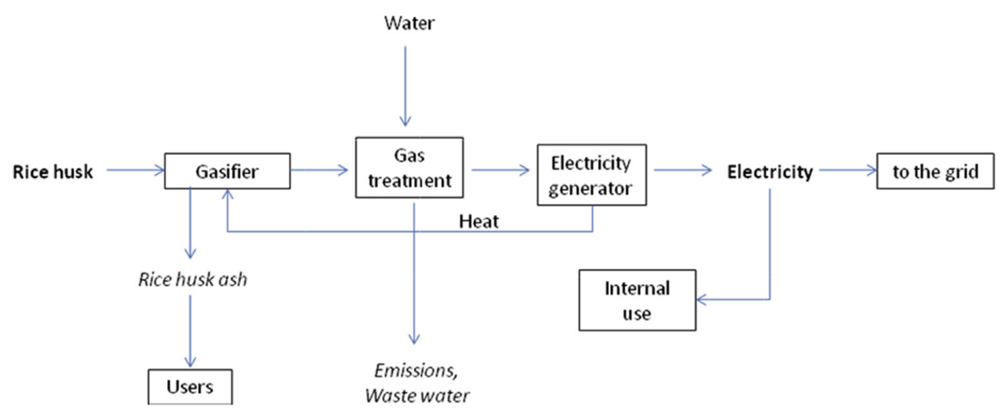

Fig. 2. Process diagram for rice husk fuelled power generation using gasification system.

(Dinkelbach, 2000).

In Thailand, rice husk pyrolysis technology for power production is not yet established. Current research found that fast pyrolysis technology has a potential for power production (Bridgwater et al., 2002; BTG Biomass Technology Group, 2012). In fast pyrolysis process, the main product is pyrolysis oil. The process was designed and tested to maximize the pyrolysis oil for up to 75% wt. on a dry feed basis. A recent study found that maximum pyrolysis oil yield derived from rice husk is up to 50% wt. (Fukuda, 2015). Combustion of pyrolysis oil was successfully tested for heat production on a large scale, including co-firing in power plants (Bridgwater et al., 2002; Chiaramonti et al., 2007).

There are several fast pyrolysis reactor configurations available. The fluidized bed configuration is the most popular, mostly with bubbling beds. In general, fast pyrolysis reactors require feed pretreatment to reduce feedstock size. After pretreatment, feed is dried before entering the reactor to reduce moisture content of the feed, and therefore to improve the quality of the oil product. The gas and char produced in the reactor can be used to provide heat back to the pyrolysis process, or it can be exported for feed drying (Bridgwater et al., 2002). Flue gas emission from feed burning is generated in the reactor. Process diagram for rice husk fuelled power generation using pyrolysis system is presented in Fig. 3.

3.2. Rice husk ash characterization

Rice husk ash is the solid residue from burning rice husk. Its high content of silica (SiO_2) is a very beneficial feature (Muthadhi et al., 2007). The burning condition of rice husk is the key factor affecting how the ash can be used. There are two forms of rice husk ash; i.e. the crystalline and amorphous, which are useful for different applications. While amorphous silica is useful in the cement, construction, and rubber industries (Mehta and Pitt, 1976), crystalline silica is useful for products such as steel, ceramics and refractory bricks (Bronzeoak Ltd., 2003).

Burning time and oxygen presence affect silica form and the surface area of the rice husk ash particles (Hwang and Chandra, 1997). Amorphous silica which has a high surface area, can be produced by using burning temperatures of below 700 °C. Amorphous silica can also be obtained by using burning temperatures of lower than 500 °C with oxygen over a prolonged stage (Muthadhi et al., 2007). Crystalline silica can be produced with burning temperatures of over 800 °C (Hwang and Chandra, 1997).

Power generation technology can affect the characteristics of

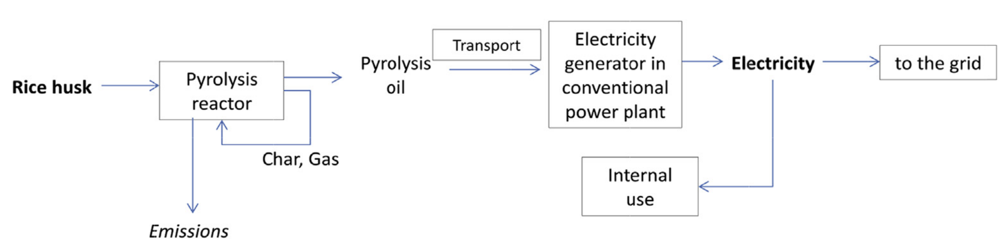

Fig. 3. Process diagram for rice husk fuelled power generation using pyrolysis system.

rice husk ash. A study by Fernandes et al. (2016) shows the chemical composition, loss on ignition, total carbon, specific weight and specific surface area of rice husk ash from different combustion technologies. Their results suggest that the chemical compositions and specific weight of all rice husk ash types investigated are quite similar. The key parameters affected by these combustion techniques are surface area, loss on ignition (LOI), SiO_2 and total carbon content. These affected parameters imply that the ash generated from different combustion technologies is suitable for different applications (Fernandes et al., 2016).

3.3. Rice husk ash uses

It has been discussed earlier that different forms of rice husk ash are useful for different applications. This section describes rice husk ash applications based on forms of rice husk ash.

3.3.1. Amorphous rice husk ash

Amorphous silica is reactive, and this feature can be valuable in many applications. For example in concrete production, amorphous rice husk ash is used to improve performance. Strength of the concrete is increased by the chemical reaction between the amorphous silica in rice husk ash and chemicals in Portland cement (Hwang and Chandra, 1997). Several studies from different countries have attempted to produce amorphous silica from rice husk for use in concrete production (Allen, 2005; Kizhakkumodom Venkatanarayanan and Rangaraju, 2015; Maeda et al., 2001; Mehta and Pitt, 1976; Salazar-Carreño et al., 2015).

To help with cost saving, amorphous rice husk ash is also used as substitute material for Portland cement and aggregates in low cost building block production in different countries (Cook et al., 1977; Nair et al., 2006; Stroeven et al., 1999). Amorphous silica from rice husk ash can also be used as cement admixture in the solidification of hazardous wastes (Asavapisit and Macphee, 2007; El-Dakroury and Gasser, 2008). In addition, it can be used as a filler in rubbers/plastics/polymers (Costa et al., 2006; Ishak et al., 1997). However, this application has not yet been tried at an industrial scale. More details of application of amorphous rice husk ash have been described in Prasara-A (2010).

3.3.2. Crystalline rice husk ash

Crystalline silica has a special feature of resistance to burning which is useful in steel, thermal insulator, refractory brick and ceramic production (Gonçalves and Bergmann, 2007; Kurama and Kurama, 2008; Siqueira et al., 2009). More details of application of crystalline rice husk ash have been described in Prasara-A (2010). Moreover, crystalline rice husk ash has been reported to be successfully used at a commercial scale as an insulator in the steel industry (Bronzeoak Ltd., 2003).

3.3.3. Other applications

Apart from the main rice husk ash applications discussed before, some other minor uses and development of several advanced uses of rice husk ash have also been identified in the scientific literature. For example, to produce bio-filter for waste water treatment, as adsorbent, as soil conditioner, as insecticide, in bio-fertilizer production, in silica gel production, as ingredient in lithium batteries, in graphene production, as a composite in polypropylene production, as activated carbon, in zeolite production, in semiconductor production, etc. (Beagle, 1978; Bronzeoak Ltd., 2003; Chareonpanich et al., 2004; International Rice Research Institute, 2016; Kanjanawarawanich, 2012; Pode, 2016; Yam and Mak, 2014).

3.3.4. Applications of rice husk ash generated from power plants

Technology used in rice husk fuelled power plants affects how the ash can be used. Fernandes et al. (2016) suggested that rice husk ash produced from moving grate technology is suitable for use as adsorbent as it has larger specific area than ash from other combustion technologies. On the other hand, the ash from fluidized bed could be used as filler in polymeric composites and in the synthesis of innovative ceramic compounds. The great amount of amorphous silica in rice husk ash from suspension fired technology makes it useful for use as pozzolanic material construction industry and use in zeolite production.

In addition to the combustion technology used in the rice husk power plant, the ash collection technique can also affect the properties of the ash. Thepnoo (2006) showed that combustion technologies and ash collection techniques are key factors affecting the properties of the ash from different rice husk based power plants in Thailand. For example, bulk density and fineness of the rice husk ash from power plants using different combustion technologies and ash collection techniques are relatively different. Moreover, fly ash and bottom ash from the same rice husk power plant have quite different silica content, bulk density and fineness. These factors should also be taken into consideration for rice husk ash management.

4. Sustainability assessments of rice husk ash applications

This section reviews sustainability assessments of various rice husk ash applications. An attempt has been made to identify all environmental, economic and social impacts of rice husk ash applications reported in the selected references. Data in Table 2 presents how the ash is used in different applications (partial or fully used), their substituted products; and identifies sustainability dimensions (environment, economic and social) considered for each study.

It is seen that many research papers while claiming sustainable/eco-friendly/environmental-friendly/green applications of rice husk ash only report technical performances of the products. All those reported that rice husk ash is successfully used in different applications considering the technical viability. Some research papers assess both technical and environmental aspects of the products. Only few papers assess technical, environmental and economic aspects of rice husk ash products. Social assessment of rice husk ash products is hardly found.

4.1. Environmental aspects

A summary of environmental performances of different rice husk ash applications is presented in Table 3. From results of the selected references, it is difficult to compare environmental performances of different rice husk ash uses. This is because each study uses different indicators for environmental assessments. Moreover, environmental performances of rice husk ash applications from different studies are not assessed on the same basis. Some studies compare environmental performances of rice husk ash uses with that of their conventional products. It was reported that rice husk ash could help reduce environmental impacts when used to substitute conventional products. Some studies compare environmental performances of different alternatives for same rice husk ash product (Balo, 2015). For this, environmental data can be used as supporting information for decision-making.

4.2. Economic and social aspects

A summary of economic performances of different rice husk ash applications is presented in Table 4. Like environmental performance, the economic results from the selected references could not be compared. This is because those studies use different economic

Table 2
Summary of reports on sustainability performances of rice husk ash applications.

Application	Partial/fully used	Substituted product	Tech. results	Env. results	Econ. results	Soc. results	Reference
High performance concrete	Partial	Portland cement	Reported	–	Reported	–	(Isaia, 2000)
Silica powders	Fully	Commercial silica	Reported	–	–	–	(An et al., 2010)
Concrete	Partial	Portland cement	Reported	Reported	–	–	(Gursel et al., 2015)
Silica	Fully	Sodium carbonate powder and quartz	Reported	–	–	–	(Liu et al., 2011)
Activated carbon	Fully	Commercial activated carbon	Reported	–	–	–	(Liu et al., 2011)
Pb and Zn stabilization	Fully	Commercial adsorbents	Reported	–	–	–	(Bosio et al., 2014)
Porous silica	Fully	Water glass	Reported	–	–	–	(Ahmad-Alyosef et al., 2014)
Soil conditioner	Partial	N fertilizer	–	Reported	–	–	(Prasara-A and Grant, 2011)
Brick	Partial	clay	–	Reported	–	–	(Prasara-A and Grant, 2011)
Concrete block	Partial	Portland cement	–	Reported	–	–	(Prasara-A and Grant, 2011)
Concrete	Partial	Portland cement	Reported	–	–	–	(Zunino and Lopez, 2016)
Concrete	Partial	Portland cement	Reported	–	–	–	(Kizhakkumodom Venkatanarayanan and Rangaraju, 2015)
Epoxy coating	Partial	Epoxy paint	Reported	–	–	–	(Azadi et al., 2011)
Insulator	fully	Commercial insulator	Reported	Reported	Reported	–	(Balo, 2015)
Heat absorbing glass	Fully	Sand	Reported	–	–	–	(Berkin, 2008)
Brick	Partial	Natural sand	Reported	–	–	–	(Hwang and Huynh, 2015)
Mortar coating	partial	Portland cement	Reported	Reported	–	–	(Mendes Moraesa et al., 2010)
Concrete	Partial	Portland cement	Reported	–	–	–	(Antiohos et al., 2013)
Concrete	Partial	Portland cement	Reported	–	Reported	–	(Khan et al., 2012)
Concrete	partial	Portland cement	Reported	Reported	–	–	(Rahman et al., 2014)
Rice mill wastewater treatment	Fully	Commercial adsorbents	Reported	–	–	–	(Kumara et al., 2015)
Pure white silica	Fully	Commercial silica	Reported	–	–	–	(Kumara et al., 2015)
Bio-char	Fully	Charcoal	Reported	reported	Reported	Reported	(Shackley et al., 2012a; Shackley et al., 2012b)
Sand–cement block	Partial	Clay brick	Reported	–	Reported	–	(Lertsatitthanakorn et al., 2009)

Tech. = Technical; Env. = Environmental; Econ. = Economic; Soc. = Social.

Table 3
Summary of environmental performances of rice husk ash applications.

Application	Substituted product	Indicators	Compared with	Results	Reference
Concrete	Portland cement	- GWP	Conventional concrete	Use of rice husk ash helps reduce GWP.	(Gursel et al., 2015)
Soil conditioner Brick Concrete block	N fertilizer Clay Portland cement	- Climate change - Ozone depletion - Acidification - Eutrophication - Human toxicity - Photochemical oxidant formation - Particulate matter formation - Ecotoxicity - Land occupation - Water depletion - Metal depletion - Fossil fuel depletion	Among different rice husk ash use options; soil conditioner, brick, concrete block production and landfill	Use of rice husk ash in concrete block production shows best environmental performance among options investigated.	(Prasara-A and Grant, 2011)
Insulator	Commercial insulator	- CO_2 - SO_2	Among four different energy types used (natural gas, fuel-oil, coal, and LPG)	- CO_2 emission varies between 22.25 and 9.97 kg/(m^2yr) - SO_2 emission varies between 19.37 and 0.03 kg/(m^2yr)	(Balo, 2015)
Mortar coating	Portland cement	- Operating situation - Frequency or probability of aspects - Impact occurrence - Severity - Degree of risk	Conventional mortar	Use of rice husk ash helps reduce environmental impacts.	(Mendes Moraesa et al., 2010)
Concrete	Portland cement	- Carbon footprint	Conventional concrete	Use of rice husk ash helps reduce carbon footprint.	(Rahman et al., 2014)
Bio-char	Charcoal	- Environmental contaminants - Carbon abatement	–	- Environmental contaminants are assessed for use in process improvement - carbon abatement from rice husk char addition is approximately 0.42tCO_2 t^{-1} rice husk	(Shackley et al., 2012a; Shackley et al., 2012b)

Table 4
Summary of economic performances of rice husk ash applications.

Application	Substituted product	Indicator	Compared with	Results	Reference
High performance concrete	Portland cement	Equivalent cost of cement	- Among different mixtures of rice husk ash, cement, fly ash and silica fume	Mixtures with more pozzolans (including rice husk ash) have lower costs.	(Isaia, 2000)
Insulator	Commercial insulator	Payback period	- Among four different energy types used (natural gas, fuel-oil, coal, and LPG)	Payback periods are 3.62, 2.28, 2.02 and 1.88 yr respectively.	(Balo, 2015)
Bio-char	Charcoal	Economic value	–	Economic value varies from \$9 t^{-1} (including only recalcitrant carbon) to \$15t^{-1} (including avoided emissions from energy production).	(Shackley et al., 2012a; Shackley et al., 2012b)

indicators. However, it shows that rice husk ash can help save production cost as reported in Isaia (2000). In the study of Balo (2015), payback periods of different options in producing insulator from rice husk ash are assessed. This can be useful for decision makers.

Regarding social aspect, only one study reported social issue of rice husk ash use. Health and safety issues are reported in the study on rice husk char production (Shackley et al., 2012a, 2012b). It was pointed out that the health impact of concern is exposure to crystalline form of rice husk ash. However, further tests are suggested to determine the extent of amorphous and crystalline portions in rice husk char.

Based on the literature found, environmental, economic and social performances of some rice husk ash applications are reported. However, only some sustainability indicators are assessed for some rice husk ash applications. In addition, the sustainability performances of rice husk ash applications found from literature are not comparable since they are assessed using different indicators. Further comparison of sustainability characteristics of different rice husk ash applications using same indicators and units is essential.

4.3. Triple bottom line assessment

To ease decision making, an attempt has been made to compare sustainability performances of different rice husk ash applications. Following the "triple bottom line" framework, all environmental, economic and social performances of the rice husk ash applications are needed to be taken into account. Several environmental, economic and social indicators are available. However, only main indicators such as reduction in greenhouse gas emissions, cost saving and employment generation are selected for consideration. These indicators are selected based on their significance and their data availability. Note that only rice husk ash use options where the ash is fully used in the process, and options having results for all indicators proposed are reported in this section.

Reduction in greenhouse gas emissions is sought by finding out how much greenhouse gas (GHG) emission can be reduced by replacing the conventional products by rice husk ash. Greenhouse gas emissions reduced is the amount of greenhouse gases released by using the conventional products. The amount of greenhouse gases released along the life cycle of products are sourced from the Thailand Greenhouse Gas Management Organization (2016) and Ecoinvent 2.2 database, analyzed by IPCC 2007 GWP 100a method. It is reported in the unit of kg CO_2 equivalent per tonne of conventional products.

Cost saving is the estimated cost that can be saved by replacing the conventional product by rice husk ash. Assuming that the ash is free of charge, this is just the price of the conventional products. Where standard prices are available, they are acquired from databases of the Bureau of Trade and Economic Indices (Bureau of Trade and Economic Indices, 2016a, b). For products that have no standard prices, current prices are sought by internet survey. It is reported in the unit of Thai baht (THB) per tonne of conventional product.

Employment generation is sought from Silalertruksa et al. (2012). This is reported in the unit of person-years employed per million Thai Baht spent in the economic sector. The sector identified is the industry using rice husk ash in their production processes. The economic sectors shown in Table 5 are selected from the list given in Silalertruksa et al. (2012). Estimated GHG reduction, cost saving and employment generation for each rice husk ash

Table 5
Triple Bottom Line results of rice husk ash applications.

Application	Economic sector	Substituted product	GHG reduced (kg CO_{2eq}/t product)	Cost saved (THB/t product)	Employment generated (person-years/M THB)
Concrete	Cement and concrete	Portland cement	760.0	2694	1.57
Silica powders	Basic Industrial Chemicals	Commercial silica	22.30	1000–4000	2.04
Activated carbon	Basic Industrial Chemicals	Charcoal	1005	5000–8000	2.04
Metal stabilization	Other Services & Unclassified	Portland cement	760.0	2694	4.69
Soil conditioner	Paddy, Maize, Cereals	Lime	1068	1100–1200	16
Brick	Other Services & Unclassified	Sand	3.700	292	4.69
Insulator	Iron and Steel products	Fire brick	241.0	4700	1.14
Heat absorbing glass	Ceramic, Glass and Other non-metallic products	Sand	3.700	292	2.19
Rice mill wastewater treatment	Other Services & Unclassified	Charcoal	1005	5000–8000	4.69
Bio-char	Other Services & Unclassified	Charcoal	1005	5000–8000	4.69

THB = Thai Baht, the currency of Thailand; 1 THB is equal to approximately 0.029 US Dollar (at July 2016).

applications are presented in Table 5.

The results in Table 5 suggest that using rice husk ash to substitute for charcoal can help to reduce largest amount of greenhouse gases; and save the largest cost compared to other options. Using rice husk ash to replace charcoal in different sectors has a slightly different impact on employment generation. Using the ash in basic industrial chemical sector generates lower employment when compared to other services and unclassified sector. Based on review data in Table 5, it is suggested that using rice husk ash to substitute charcoal is the most sustainable option. However, there are also other important sustainability indicators to consider such as fossil fuel depletion, human toxicity, ecotoxicity, particulate matter formation, total net profit (TNP), total value added (TVA), and incomes of workers involved in production processes. Moreover, other factors such as rice husk ash properties, transportation of rice husk ash, infrastructure and technology for rice husk ash applications are also needed to be taken into consideration.

5. Conclusions

The sustainability characteristics of various rice husk ash utilization have been reviewed and reported. Many research papers, claiming sustainable/eco-friendly/environmental friendly/green applications of rice husk ash, report only technical performances of rice husk ash products. Only few papers also considered environmental and economic aspects of rice husk ash uses. Reporting on social issues of rice husk ash use was hardly found and thus should be considered for future studies.

In addition, this paper compared sustainability performances of rice husk ash applications following "triple bottom line" framework. All environmental, economic and social indicators i.e. greenhouse gas emissions reduction, cost saving and employment generation were considered. It is suggested that using the ash to substitute for charcoal is the most sustainable option. However, other sustainable indicators such as fossil fuel depletion, human toxicity, ecotoxicity, particulate matter formation, total net profit (TNP), total value added (TVA), and incomes of workers should be considered in the future research. Moreover, further study on other factors such as rice husk ash properties, transportation of rice husk ash, infrastructure and technology for rice husk ash applications are also needed.

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