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

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ABSTRACT

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 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.

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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

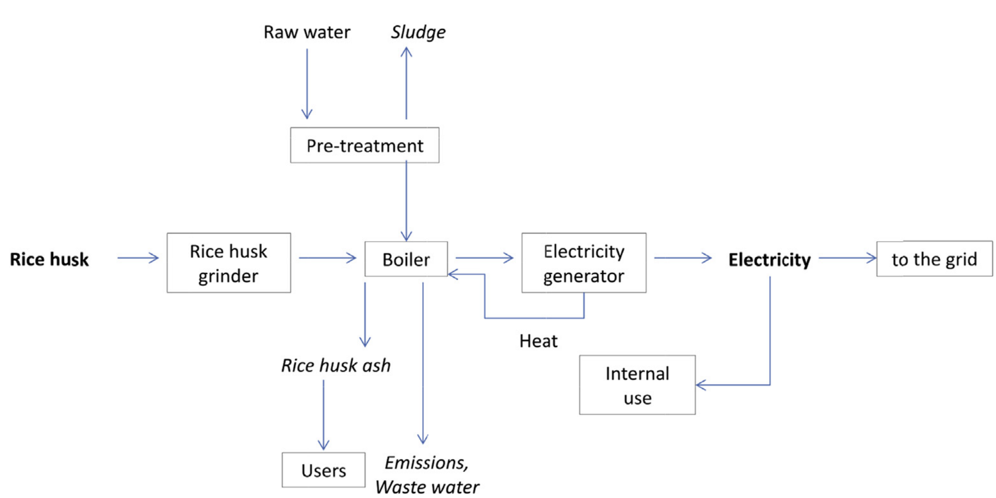

Fig. 1. Process diagram for rice husk fuelled power generation using combustion system.

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).

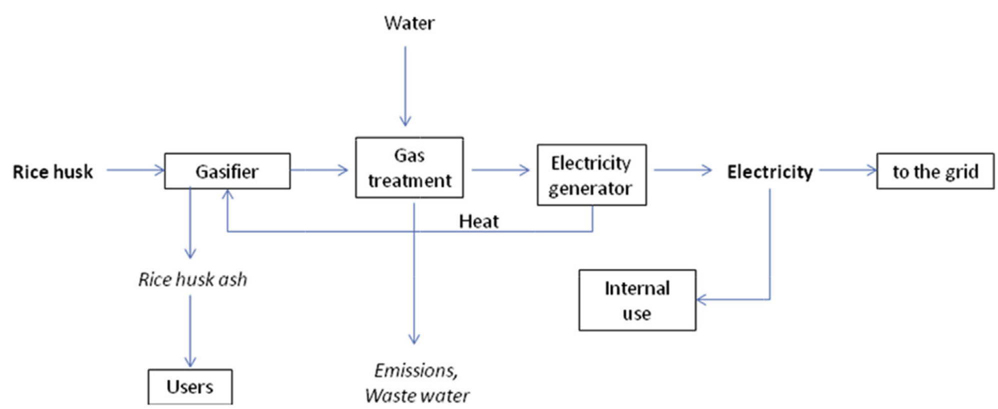

Fig. 2. Process diagram for rice husk fuelled power generation using gasification system.

(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

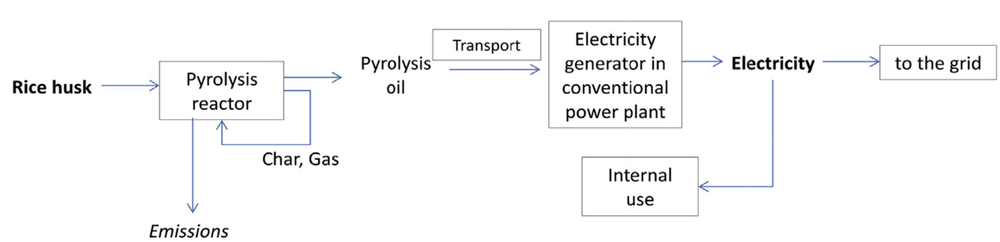

Fig. 3. Process diagram for rice husk fuelled power generation using pyrolysis system.

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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