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LIFE CYCLE ASSESSMENT OF BIO-BASED THERMAL INSULATION MATERIALS FORMED BY DIFFERENT METHODS

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Abstract

Inorganic thermal insulators are commonly used to improve energy efficiency. However, environmental and health aspects of their production until the end of life have been increasingly concerned. Agricultural wastes including rice straw, rice husk and corn cobs are abundant in Thailand and converted into value-added products such as thermal insulation materials offers a viable recycling opportunity as the ecological burden of a product has now become a widely-discussed issue. In this paper, global warming potential impact of thermal insulation materials made from agricultural wastes; rice straw, bagasse, coconut coir and oil palm fibre, were assessed by using IPCC 2007, while Eco-indicator 99 was applied to evaluate the endpoint impact. Moreover, those impact of three different forming processes including (i) hot-pressing, (ii) using concentrated latex as a binder and (iii) using mixed concentrated latex-chemicals as a binder were compared. The physical properties of the insulation pads were tested to identify qualities such as density, water absorption, thickness swelling, fire resistance and thermal conductivity. The eco-efficiency of the insulation pads was also measured the performance and environmental impact and compared with commercial thermal insulators. Results revealed that thermal insulators formed by mixed concentrated latex-chemicals had the lowest thermal conductivity, while those formed by hot-pressing had the highest. Thermal conductivity of the four agricultural waste thermal insulation materials varied between0.042–0.087 W/mK. Insulators made from rice straw caused the greatest environmental impact followed by those made from bagasse, coconut coir and oil palm fibre respectively. The result of eco-efficiency of oil palm fibre insulator, formed by mixed concentrated latex-chemical, was best presented and closed to the eco-efficiency of commercial thermal insulators.

Key words: agricultural waste, concentrated latex, hot-pressing, life cycle assessment, thermal insulation

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1. Introduction

The domestic construction business has been increasingly and led to an increase in demand for insulation. Currently, approximately 90% of the thermal insulators are domestically produced. Most of them are fibre glass and plastic foam type insulation. Over the years, the environmental and health aspect arising during the production until the end of life of insulating materials (Papadopoulos and Giama, 2007; Spranceana et al., 2017). Papadopoulos (2005) studied the environmental and health aspects of insulation materials and found that fibre glass causes carcinogenic, organic foamy such as polyurethane, expanded polystyrene emit HCFCs. Due to the environmental concern, thus the organic based insulation materials have been increasingly investigated (Binici et al., 2014; Nechita and Ionescu, 2017).

Thailand is an agricultural country with almost half of its land area under cultivation. As a result, agrarian residue or wastes such as rice straw, bagasse, coconut coir, corn cobs, cassava stems and oil palm fibre are abundant. Many attempts have been made to reuse these waste materials including converting them to animal feeds (Nigussie et al., 2015), as fertilizers

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(Agele et al., 2011) or even for bio-based energy (Sarkar et al., 2012). However, certain agricultural wastes cannot be utilized in these ways and are disposed in landfills or burnt resulting in negative environmental impacts including air pollution. In 2013, more than 62 million tonnes of agricultural wastes remained after secondary use (DAEDE, 2013). Several researchers have investigated recycling agrarian wastes into useful useable products, including thermal insulation processed from organic fibrous materials (cellulose, cotton, wood, pulp, cane) and cellular materials (cork, foamed rubber, polyethylene, polyurethane and other polymers) (Zhou et al. 2010). Various agricultural wastes can be processed into bio-based thermal insulation materials including cotton stalk fibre (Zhou et al., 2010), coconut husk (Manohar, 2012; Panyakaew and Fotios, 2011), bagasse (Manohar, 2012; Panyakaew and Fotios, 2011; Usubharatana and Phungrassami, 2015), date palm fibre (Chikhi et al., 2013), rice straw (Boonterm et al., 2016; Usubharatana and Phungrassami, 2015; Wei et al., 2015), sunflower stalk (Binici et al., 2014; da Rosa et al., 2015), rice husk (da Rosa et al., 2015), waste rubber (Abdel Kader et al., 2012), corn stalk (Binici et al., 2016), waste olive seeds (Binici and Aksogan, 2016), oil palm (Manohar, 2012; Sihabut and Laemsak, 2010), pineapple leaves (Tangjuank, 2011) and corn cobs (Pinto et al., 2012). It can be concluded that over the past 10 years, research and efforts have been studied to investigate and develop various types of agricultural residues to thermal insulators.

To produce a bio-based thermal insulator, the agricultural wastes must undergo a fibre extraction process. This can be performed through chemical treatments using alkali solutions or physical treatments such as steam and irradiation (Chen et al., 2011) to remove lignin from the natural fibres. Paul et al. (2008) studied banana fibre under different chemical treatments including sodium hydroxide (NaOH), benzoyl chloride (C_6H_5COCl) and potassium permanganate ($KMnO_4$). Johar et al. (2012) used NaOH to remove lignin from rice husk fibres. Alkaline solutions have been commonly used to remove lignin. After lignin extraction, the fibres undergo a forming process mainly through two methods with or without a binder.

Parkash (2015) studied banana leaves with a binder consisting of epoxy and waste plastics to produce thermal insulators, while Doost-Hoseini et al. (2014) used urea-formaldehyde and melamine-urea-formaldehyde as binders to form bagasse fibre into sound absorbing material. Epoxy resins are widely used as binders with many fibre composites such as corn stalk to produce building insulation (Binici et al., 2016) and pineapple leaf and banana fibres to fabricate fibre-reinforced composites (Shih et al., 2012). Despite recent advances in the development of insulator production, processing systems involving fibre extraction and formation pose adverse environmental impacts, for example, formaldehyde is still used as a synthetic binder despite being a known human carcinogen (Charoenvai, 2013). Using of chemical solutions for fibre extraction also causes similar negative consequences. Hence, environmental impact has now become a significant concern regarding product development methods. Some research has been undertaken on green composites, especially pertaining to the selection of natural fibres extracted from wastes rather than from valuable crops (Zini and Scandola, 2011). Chitosan extracted from shrimp shell was processed as a binder for a bio-based composite of shredded sunflower stems and used for thermal material (Mati-Baouche et al., 2014). Palumbo et al. (2015) studied crop by-products such as rice husk, corn pith and barley straw to make thermal insulation material using corn starch with sodium alginate as a binder. Another binder, widely used to replace synthetic products is natural latex. This is abundant in Thailand which is a world leader in native rubber production. Jaktorn and Jiajitsawat (2014) used natural rubber latex as a binder to make thermal insulation from water hyacinth fibres. Tangjuank (2011) studied the thermal insulation properties of a panel made from pineapple leaves bound by natural latex. Jintakosol and Kumfu (2012) conducted research on the thermal insulation properties of durian peel fibres with natural latex as the binder material.

The literature review of forming insulator without binder such as Panyakaew and Fotois (2011) applied a hot-pressing method to form thermal insulation boards from coconut husk and bagasse without binding additives to avoid the use of chemicals, while Zhou et al. (2010) fashioned particleboards by transforming stalks from cotton production residue into fibres without any chemical binder.

Whether a product is environmental friendly, its information of production process and raw material acquisition would be analysed by a life cycle assessment (LCA). LCA has been applied to a wide range of natural fibre composites to assess the environmental impacts caused by each product (Riedel and Nickel, 2003). LCA methodology was used to compare the environmental impacts of wood-fibre-reinforced composite and polypropylene (Xu et al., 2008), the results found that wood-fibre-reinforced composite seem to be superior environmental friendliness compared to polypropylene. While La Rosa et al. (2014) analysed the LCA of an eco-sandwich made of bio-based epoxy resin versus a traditional sandwich made of epoxy/glass fibres. The LCA of hemp cultivation and use of hemp-based thermal insulation materials in buildings was investigated by Zampori et al. (2013) and Florentin et al. (2017). However, the comparison of LCA between thermal insulation materials made from agricultural wastes with a natural latex binder and insulation materials formed by hot-pressing has not yet been reported.

This research aims to analyse the life cycle of insulation materials made from agricultural wastes including rice straw, bagasse, coconut coir and oil palm fibre which are all abundant in Thailand. Three forming processes were investigated as (i) hot-pressing, (ii) using concentrated latex as a binder and (iii) using mixed concentrated latex-chemicals as a binder. All processes were documented to assist in the development of a more environmentally friendly insulator. Each type of insulator offered different parameters of density, water absorption, thickness swelling, fire resistance and thermal conductivity. Moreover, the eco-efficiency of these insulators was considered and discussed.

2. Material and methods

Life Cycle Assessment methodology was developed in compliance with international standards ISO14040 (2006) and ISO14044 (2006) evaluate the environmental burdens including resources consumed throughout the entire life cycle of products or processes. Not only one part, but the whole production process was holistically assessed starting from raw material acquisition, manufacturing, distribution, use and disposal (also called cradle to grave). The outcome of the assessment highlighted the hotspots relating to the products or activities throughout the whole life cycle which then enabled the initiation of appropriate plans for improvement. An LCA encompasses four steps as goal and scope, life cycle inventory, life cycle impact assessment and interpretation.

2.1. Goal and scope

This research aimed to assess the environmental impacts caused by the production of thermal insulation materials made from agricultural wastes based on LCA following ISO14040. Three forming processes were analyzed as (i) hot-pressing, (ii) using concentrated latex as the binder and (iii) using mixed concentrated latex-chemicals as the binder. Agricultural wastes focused on rice straw, bagasse, coconut coir and oil palm fibre. A large amount of Thailand's agricultural waste left after harvesting as shown in Table 1. Where rice is the major agricultural product, the area of annual harvested rice paddies is about 13.28 million ha (Liese et al., 2014). Over 90% of the rice during the high harvesting season (November-December) are burned (Tapayarom and Thi Kim Oanh, 2007). In year 2015, Thailand was the world's second largest sugar exporter which produced approximately 11.3 million tons of sugar (Boonmee and Pongsamana, 2017). Although, small amount of bagasse, coconut coir and oil palm fibre are left. This is because these industries use residues as alternative fuel.

However, if considering the amount of primary agricultural wastes, the remaining amount is interesting to bring more valued products.

Rice straw is a by-product from dried rice plants after harvesting. Bagasse is a fibre remaining after extraction of sugar juice from sugarcane. Coconut fibre or coconut coir is a fibre extracted from the husk of the coconut. Oil palm fibre is a by-product from fresh palm fruit after crude palm oil extraction. The system boundary started from cultivation to raw fibre extraction. For example, rice farming with rice straw was considered as a by-product (system boundary 1) with fibre preparation, thermal insulation production and disposal at end of life (shown as system boundary 2 in Fig. 1).

The complete process was holistically assessed to determine the total environmental input and output related to LCA. System boundary 1 included both primary and secondary data associated with raw fibres. System boundary 2 data were obtained from laboratory measurements. Energy consumption during the forming process was estimated based on the running time and power consumption depending on the equipment used and wastewater was assumed to be equivalent to water consumption. The waste disposal scenario setting was stipulated as landfill which is common in Thailand.

However, since the process was at such an early stage in product development, results might be different in a large-scale production plant; however, estimating scale-up LCA results at an industrial level was beyond the scope of this study. Similarly, this primary assessment did not include transportation of raw materials during acquisition, use and disposal to eliminate bias in environmental impact assessment caused by the distance between raw fibres and the laboratory. However, transportation was discussed and analyzed to assess the overall picture.

Four types of materials and three forming process methods were analyzed and the functional unit (f.u.) was identified a reference for system input and output data standardization (Dylewski and Adamczyk, 2011). Once the functional unit was set, quantities or weights of product were analyzed and regarded as reference flow. The environmental efficiency of each insulator type was analyzed based on the same functional unit. An insulator provides thermal resistance (R) to prevent incoming or outgoing heat. The value of R varies depending on material properties including thermal conductivity and density. The functional unit was set at R in which area was indicated as 1 m^2.

Table 1. Potential of agricultural waste in Thailand

Agricultural residues	*Amount of residues (tons/year)*	*Residue potential (tons/year)*
Bagasse	28.026.761.54	0
Rice straw	19.005.628.14	10.892.826.89
Oil palm fiber	2.434.291.59	0
Cassava peel	8.463.711.76	0
Corn cob	1.216.078.72	120.997.14
Coconut coir	333.310.89	3.334.11

Reference: DAEDE (2013)

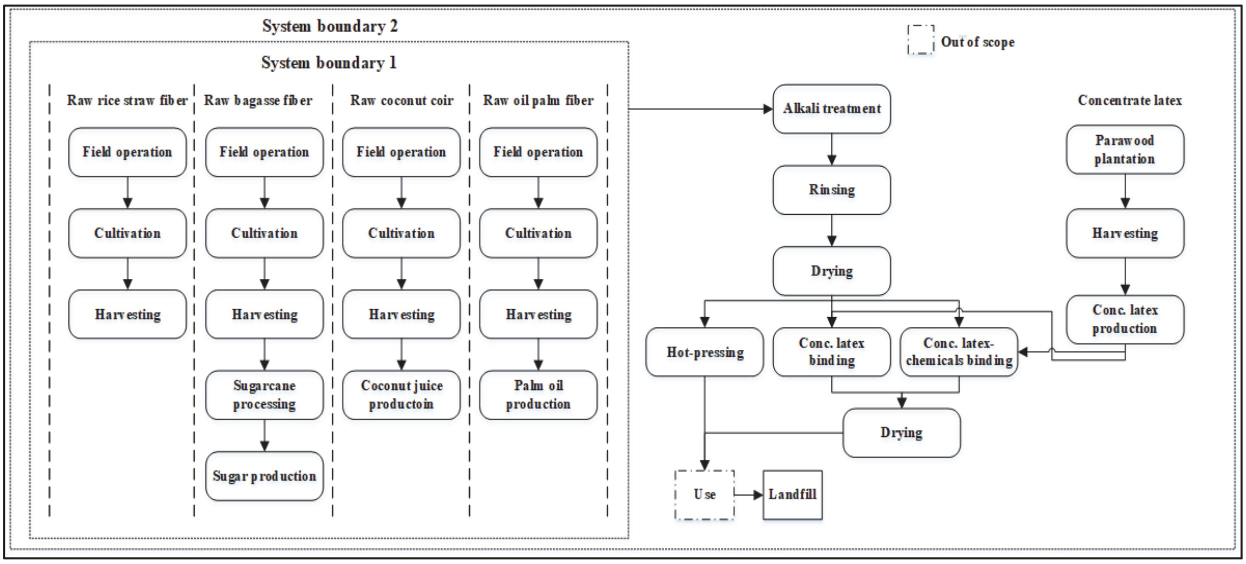

Fig. 1. System boundary

In Eq. (1), reference flow reverts the possible weight of the product to achieve R value of 1 m^2K/W.

$$f.u. = R = \frac{m}{\lambda \rho A} \tag{1}$$

where: *f.u.* represents the functional unit, *R* is the thermal resistance as 1 (m^2K/W), λ is the thermal conductivity (W/mK), ρ is the density of the insulation material (kg/m^3), *A* is the area as 1 (m^2) and *m* is the mass (kg).

The main production processes were evaluated and crucial hotspots were identified to enable the optimal choice of environmentally friendly fibres and preferable production techniques.

2.2. Life cycle inventory and properties testing

Life cycle inventory

The production process of thermal insulators throughout the entire life cycle is shown in Fig. 1. Main inputs of raw fibres were assessed as fertiliser, diesel, herbicides and insecticides. Raw rice straw fibre and raw oil palm fibre inventory data were obtained and modified from previous studies by Yodkhum and Sampattagul (2014) and Sampattagul et al., (2011). Input and output data of raw bagasse fibre and coconut coir were collected as primary data from the sugar and coconut juice industries, respectively. Production of rice straw, bagasse, coconut coir and oil palm took place less than 200 km from the laboratory. Alkali treatment the first preparation step to remove lignin and hemicellulose from the raw fibres. Agricultural wastes were cut into 5 cm pieces and mixed with 15% NaOH pellet by weight. The most appropriate reaction time was 30 minutes for rice straw, 60 minutes for bagasse, 120 minutes for coconut coir (Usubharatana and Phungrassami, 2015) and 30 minutes for oil palm fibre**.** Fibres were washed thoroughly with water to remove excess NaOH and then dried in an oven at 80 °C for 6 h (Usubharatana and Phungrassami, 2015)**.** The forming process was performed in two different ways, either using a binder or by hot-pressing. Using a binder increased product durability and the most frequently was waterborne latex (Sakthivel and Ramachandran, 2012).

Binders used were natural concentrated latex and a natural concentrated latex-chemical mixture. Concentrated latex inventory data were collected as a primary source from a latex producing plant while data regarding the concentrated latex-chemical mixture were sourced from the formula in Usubharatana and Phungrassami (2015). Dry fibres were spread out into a 20×20×3 cm mould and sprayed with latex binder with ratio between fibres and latex set at 1:2, 1:3 and 1:4. After drying in an oven at 100°C for 45 minutes, the latex stabilised and chemically bonded with the fibres. The product was then cut into various sample sizes to test for thermal insulation qualities. Hot-pressed fibres were also spread out into a mould and compacted in a pressing machine at a controlled temperature, pressure and time. To determine the optimal formation time, coconut coir was trialed at temperatures of 120, 130, 140 to 200 °C, with reaction time 5, 10, 15 to 45 min and pressures of 10, 20, 30 and 60 kg/cm^2. Results suggested that the optimal condition for hot-pressing was 130 °C at 10 kg/cm^2 for 5 min and the other fibre types were also hot-pressed under these conditions.

The summary of data requirements for performing LCA as shown in Table 2. The installation process was exclude from the LCA, since this study was only a comparative analysis. The disposal scenario was landfill at the end of product lifetime since incineration is not common in Thailand. Product formation resulted in 28 different insulating materials. Table 3 indicates each type of insulator together with abbreviations used in this study. To illustrate, the insulator made from rice straw with concentrated latex binder at ratio 1:2 fibre to binder was abbreviated as R(1:2). The samples of prepared thermal insulators can be presented in Fig. 2

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Table 2. Data requirements and sources for performing LCA

Life cycle stage	***Data and Data requirements***	***Data sources***
Raw fibre production		
Raw rice straw fibre Raw oil palm fibre Raw bagasse fibre Raw coconut coir fibre	Fertilisers, herbicides and insecticides, fuel oil, yield Fertilisers, herbicides and insecticides, fuel oil, electricity, yield 0.0335 kg CO_2eq / kg fibre 1.24 mPt / kg fibre 0.0216 kg CO_2eq / kg fibre 2.20 mPt / kg fibre	Yodkhum and Sampattagul (2014) Sampattagul et al. (2011) Primary data collection* Primary data collection*
Preparation of fibre		
15% of NaOH	2.36 kg for 1 kg rice straw 1.29 kg for 1 kg bagasse 0.16 kg for 1 kg coconut coir 1.01 kg for 1 kg oil palm	Primary data collection
Electricity	29.59 kWh for 1 kg rice straw 16.88 kWh for 1 kg bagasse 2.27 kWh for 1 kg coconut coir 12.69 kWh for 1 kg oil palm	Primary data collection
Water	15.75 L for 1 kg rice straw 8.62 L for 1 kg bagasse 1.08 L for 1 kg coconut coir 6.76 L for 1 kg oil palm	Primary data collection
Preparation of insulator		
Concentrate latex (raw material) Concentrated latex-chemical mixture Electricity for drying process Electricity for hot-pressing	0.0994 kg CO_2eq / kg latex 1.97 mPt / kg latex Composition of latex and chemicals 2.25 kWh per batch 0.5 kWh per press	Primary data collection* Usubharatana and Phungrassami (2015) Primary data collection Primary data collection

**Primary data collected from private LCA projects, therefore detail LCI are confidential and do not be allowed for publishing*

Table 3. Type of acquired thermal insulators and abbreviations

Preparation method	***Fibre type***			
	Rice straw	***Bagasse***	***Coconut coir***	***Oil palm***
Hot-pressing	R	B	C	O
Concentrate latex binder				
Fibre:binder (1:2) by mass	R(1:2)	B(1:2)	C(1:2)	O(1:2)
Fibre:binder (1:3) by mass	R(1:3)	B(1:3)	C(1:3)	O(1:3)
Fibre:binder (1:4) by mass	R(1:4)	B(1:4)	C(1:4)	O(1:4)
Concentrate latex-chemical mixture binder				
Fibre:binder (1:2) by mass	RC(1:2)	BC(1:2)	CC(1:2)	OC(1:2)
Fibre:binder (1:3) by mass	RC(1:3)	BC(1:3)	CC(1:3)	OC(1:3)
Fibre:binder (1:4) by mass	RC(1:4)	BC(1:4)	CC(1:4)	OC(1:4)

(a)

(b)

(c)

(d)

Fig. 2. Samples of thermal insulators (a) rice straw (b) bagasse (c) coconut coir and (d) oil palm fibre

During data collection some assumptions were made. Seed production was outside the study scope. Sugar derived from sugarcane or extracted palm oil was considered as a mass allocation method between main product and by-product. Associated background data such as electricity grid mix production in Thailand were mainly obtained from the national life cycle inventory database (MTEC, 2014). International databases, mainly from Ecoinvent (2010) were used, if the national database was not available. Carbon dioxide (CO_2) absorbed by the plants during cultivation was not estimated, because this research is not focused on cultivation, but on waste management. During usage, the installation might involve other fixing materials; however, as the study was only a comparative analysis on laboratory scale and the products were not actually used, therefore the usage stage was not considered for analysis. At end of life, the insulation pads were assumed to be disposed by landfill.

Properties of insulation materials

Twenty eight specimens of different compositions and materials were used for properties tests including density, water absorption, thickness swelling, fire resistance and thermal conductivity.

Water absorption

Water resistance of bio-based materials is an important parameter (Chikhi et al., 2013). This test consisted on putting samples in a bath filled with distilled water until the samples became saturated. Water absorption value was determined using Eq. (2):

$$\text{Water absorbtion (\%)} = \left[\frac{(W_2 - W_1)}{W_1}\right] \times 100 \qquad (2)$$

where W_1 is the dry weight of specimen and W_2 is the weight of the sample after saturation.

Thickness swelling

Specimens with the dimension of 5 cm by 5 cm were prepared for evaluation of the thickness swelling. Before immersion in water, the specimens were measured the thickness at four points along each side at 1 cm from the edge. Then the specimens were submerged in water for 24 hours before thickness measurements were taken at the same location. The thickness swelling value was determined using Eq. (3):

$$\text{Thickness selling in water (\%)} = \frac{[t_1 - t_0]}{t_0} \times 100 \qquad (3)$$

where t_0 and t_1 are the thickness of the test specimen before soaking and soaking, respectively.

Fire resistance

Fire resistance is an essential quality of building material. All specimens underwent burn testing according with ASTM D635-03 (2003). Specimens were prepared with dimensions of 125mm by 13mm by 9mm, then hold horizontally in the horizontal burning test. The flame time from the first mark (25 mm from the ignition end) until the second mark (100 mm from the ignition end) was measured (Suardana et al., 2011). The rate of burning was determined using Eq. (4):

$$\text{Rate of burning} = \frac{60L}{t} \qquad (4)$$

where L is the burned length in millimetres between the 25 mm reference mark and where the flame front stopped, t is the elapsed time, in seconds.

Thermal conductivity

Thermal conductivity is a measure of the ability of a material to conduct heat and the efficiency of each insulation material type can be compared (Al-Homoud, 2005; Zhou et al., 2010). If thermal conductivity is low, then the insulator quality is high. Each specimen was prepared to 20cm by 20cm for the measurement of thermal conductivity using the thermal conductivity building materials model H112N measuring device by P.A. Hilton.

2.3. Life cycle impact assessment

Set functional units and data associated with the system boundary were used to assess environmental impacts based on an inventory of related inputs and outputs. The impact assessment phase was quantified by two different methodologies, (i) IPCC 2007 and (ii) Eco-indicator 99. using the SimaPro 8 software application. The impact on climate change can be measured with carbon dioxide equivalent based on global warming potential (GWP) coefficients using IPCC methodology (IPCC, 2007). Equivalent was based on a relative scale which compared other GHGs with an equivalent mass of CO_2. According to IPCC methodology, for example, GWP of CO_2 was stipulated at 1, while GWP of CH_4 was 25 (IPCC, 2007). Since GWP of CH_4 are 25 times higher than that of equivalent quantify of CO_2. However, to avoid a one-sided impact assessment, multiple impact analyses were carried out. In this study, results were expressed in a simple form by Eco-indicator 99 methodology. In Eco-indicator 99, three impact categories of damage assessment were evaluated, including human health, ecosystem quality and mineral and fossil resources (Zampori et al., 2013). The results of Eco-indicator 99 are single score indicators representing the potential impact on the environmental through different damage categories (Castell et al., 2013), usually expressed as millipoint (mPt) (Cerri et al., 2013).

2.4. Interpretation

Interpretation is the last phase of the LCA where the results are analyzed the uncertainties of the applied data by using such as sensitivity analysis and uncertainty analysis (Hauschild et al., 2018). The results of LCA sensitivity analysis identified the hotspots and evaluated the influence of data assumptions and methodological choices (de Souza et al., 2016). A scenario is sensitive toward a parameter if a small change in this parameter will result in a large change in the result. Whereas a scenario is insensitive toward a parameter if any change in this parameter will have no effect on the result (Rosenbaum et al., 2018).

The main elements were assessed as firstly, the effect of allocation method of raw fibres (scenario 1). Since, the allocation method as acquired fibre could also be considered as waste, not by-product. Thus, no allocation was required and environmental burdens caused by cultivation and fibre acquisition were excluded from the system boundary. Secondly, the effect of transportation of raw fibres and disposal of thermal insulation (scenario 2) because the transportation phase was not taken into consideration in the baseline and also how distance contributed to the environmental impacts. Thirdly, the effect of emission factors of the chemical ingredients in the chemical binder (scenario 3) because of data unavailability for the emission factor (EF) of chemicals used in concentrated latex; increases or decreases of EF were also investigated. An analyse were conducted on specimens C, C(1:2) and OC(1:2) since they caused the lowest consequential environmental impacts during each type of forming process (see the results in section 3.2) when compared with the base scenario.

2.5. Eco-efficiency

Sustainability issues have increasingly concerned. Manufacturers attempt to reduce their environmental impacts, while simultaneously delivering high value goods and services (Sproedt et al., 2015). Thus, the eco-efficiency (EE) has become a consistent tool towards the transition to sustainable development (Caiado et al., 2017). EE is "achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity" (WBCSD, 2000). EE links a product or service value to corresponding environmental impact (Li et al., 2011). EE can be expressed as Eq. (5):

$$\text{eco - efficiency} = \text{product value} \times \frac{1}{\text{environmental impact}} \quad (5)$$

Product value can be specified in various forms. For instances, Soares et al. (2013) studied waste management and set economic value as cost of waste treatment, however Li et al. (2011) set the value of building space as cubic size (m^3). Here, product value was set according to the thermal resistance of an insulation pad, while environmental impact was set as GWP. Then, EE results will be compared with EE of conventional thermal insulation materials. Three conventional thermal insulation materials such as extruded polystyrene (XPS), expanded polystyrene (EPS) and polyurethane (PUR) where thermal resistance was set at **1** and GWP values were **5.21** $kgCO_2eq$, 3.25 $kgCO_2eq$ and 3.33 $kgCO_2eq$ respectively (Pargana et al., 2014).

3. Results and discussion

3.1. Properties of bio-based thermal insulation

The qualities of the agricultural wastes used as raw materials for thermal insulators including density, water absorption, thickness swelling, fire resistance and thermal conductivity were determined.

Density

Density of the thermal insulation pads was measured as the average of three test results as (Fig. 3). Coconut coir recorded the lowest density for hot-pressing at 93.64 kg/m^3 while oil palm fibre had the highest at 361.44 kg/m^3. Increasing the latex content also increased the density as concentrated latex had a higher density than the natural fibres. Fibres derived from coconut coir from by concentrated latex produced insulation material with the lowest density, which ranged between 44.08–71.60 kg/m^3, while the other fibres ranged from 76.68–169.56 kg/m^3.

Water absorption

Water absorption of the specimens formed by hot-pressing could not be measured as they all macerated. Insulation materials formed by concentrated latex had water absorption values ranging from 73–535%. Fibres from rice straw recorded the highest water absorption at 234.92–534.85%. In contrast, oil palm fibres had the lowest absorption values at 73–153% (Fig. 4**)**, comparing to the water absorption of XPS, EPS, granulated cork, expanded clay and corn cob were 13%, 34%, 244%, 36% and 327% respectively (Pinto et al., 2012). Water absorption values reduced as the latex ratio increased which agree with findings by Jaktorn and Jiajitsawat (2014). Moreover, thermal insulation materials formed by non-chemical latex had lower water absorption than those formed by chemical bound latex. Water absorption had an inverse relationship with density and decreased with density increase as a result of the shrinking pore space. Insulation material with low density has more pore space so its water absorption is higher **(**Charoenvai et al., 2003**)**. Conversely, water absorption increased when more fibres were added which concurred with results from Chikhi et al. (2013)**.** When the proportion of fibres was equal to the latex, insulation material made from rice straw had the highest water absorption, followed by bagasse, coconut coir and oil palm respectively.

Thickness swelling

Insulation material made from bagasse recorded the highest swelling with rice straw as the lowest (Fig. 5). Insulation materials formed using mixed concentrated latex-chemicals recorded greater thickness swelling than from concentrated natural latex.

Moreover, thickness swelling showed a direct relationship with density and materials with high density also had high thickness swelling (Charoenvai et al., 2003). Thickness swelling was related to the proportion of latex, with increasing quantities of latex producing greater thickness swelling. Latex absorbed water which resulted in increased thickness of the insulation materials.

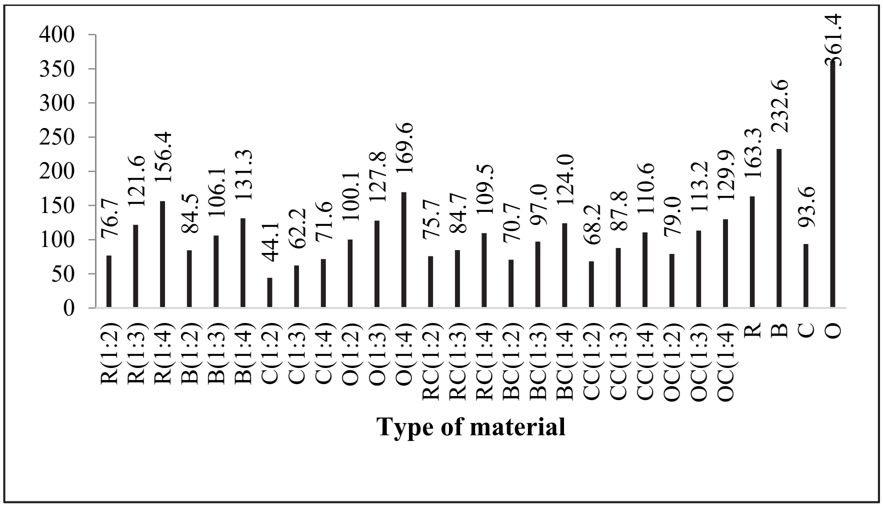

Fig. 3. Bio-based insulation material density quantification (kg/m^3)

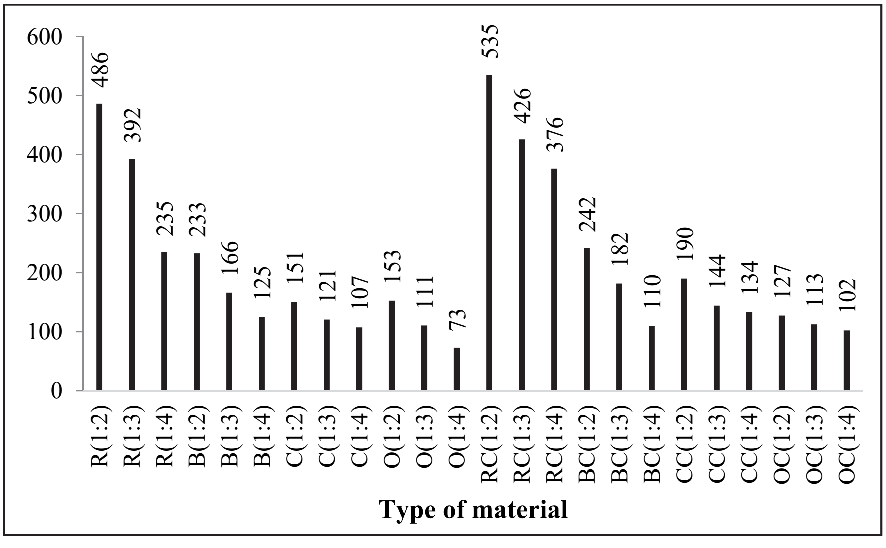

Fig. 4. Water absorption of bio-based insulation materials (%)

Fire resistance

The results can be presented as shown (Fig. 6). Natural latex had higher fire resistance than mixed latex-chemical binder. Oil palm fibre recorded the highest fire resistance (O(1:4)) and increasing the latex content resulted in higher fire resistance. Insulation materials should focus on preventing fires in buildings; however, no fire retardants were added to the specimens and the combustion rates were high.

Thermal conductivity

Thermal conductivity coefficients of the samples are given in Fig. 7. Thermal conductivity values were between 0.042–0.087 W/mK and complied with the international standard (less than 0.1 W/mK) (Binici and Aksogan, 2016). Hence, we can assume that the insulator specimens used in this test can be used in practice. Thermal conductivities of specimens formed by hot-pressing were higher than those formed by binding. Increasing the proportion of latex binder resulted in higher thermal conductivity since thermal conductivities of concentrate latex and concentrated latex with chemicals at 0.1606 and 0.1134 W/mK respectively were higher than fibre. Additionally, latex-chemical mixture binder caused lower thermal conductivity. The insulation specimen made from a 1:2 ratio of rice straw fibres and latex had a thermal conductivity of 0.058 W/mK, while a 1:2 ratio of rice straw fibres and latex-chemical mixture had a thermal conductivity of 0.053 W/mK. Test results also suggested that increasing latex content increased thermal conductivity, as space between the particles reduced; thermal conductivity of air in the spaces was lower than the particles (Jintakosol and Kumfu, 2012). The specimen made from oil palm fibre and latex-chemical mixture binder showed the lowest thermal conductivity ranging between 0.042–0.044 W/mK. Thermal conductivity of an insulator has a direct relationship with its density; the higher the density the higher thermal conductivity as a result of decreasing pore space (Khedari et al., 2004; Zhou et al., 2010). Comparison with other studies, thermal conductivities were similar for all tested fibres, but higher than fibre mad from Durian peel and other non-bio based insulators such as those made from rock wool, mineral wool or fibre glass (Table 4).

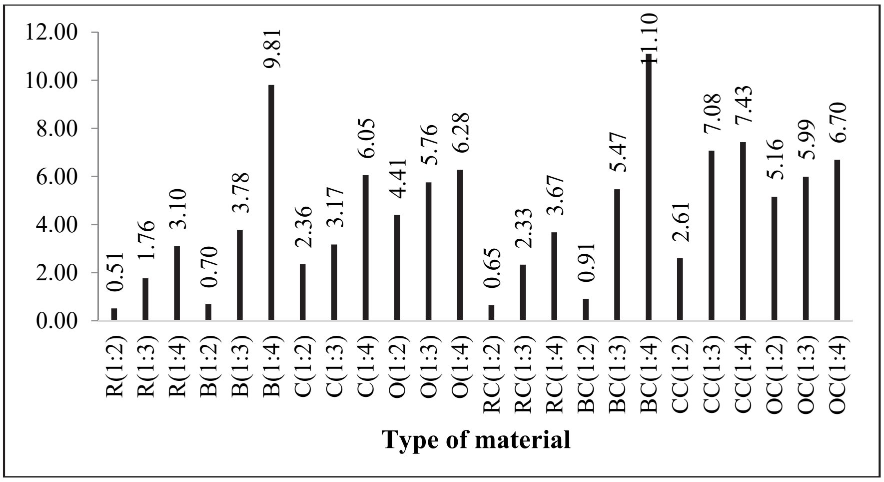

Fig. 5. Thickness swelling of bio-based insulation materials (%)

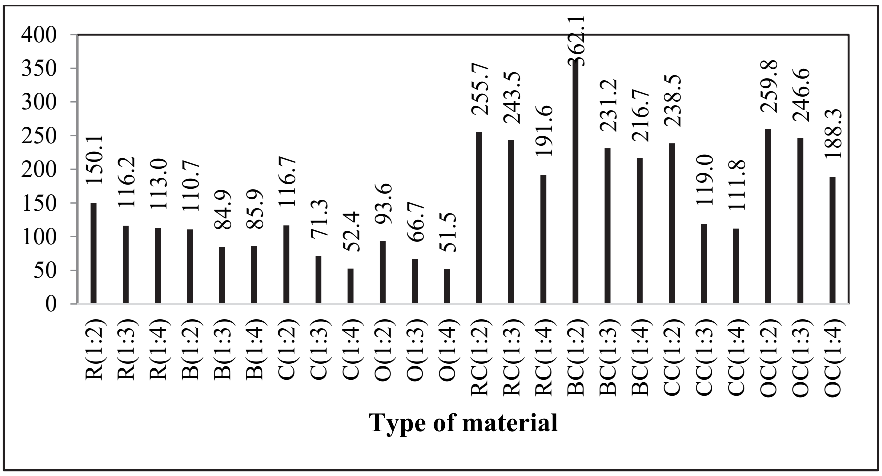

Fig. 6. Fire resistance of bio-based insulation materials (mm/min)

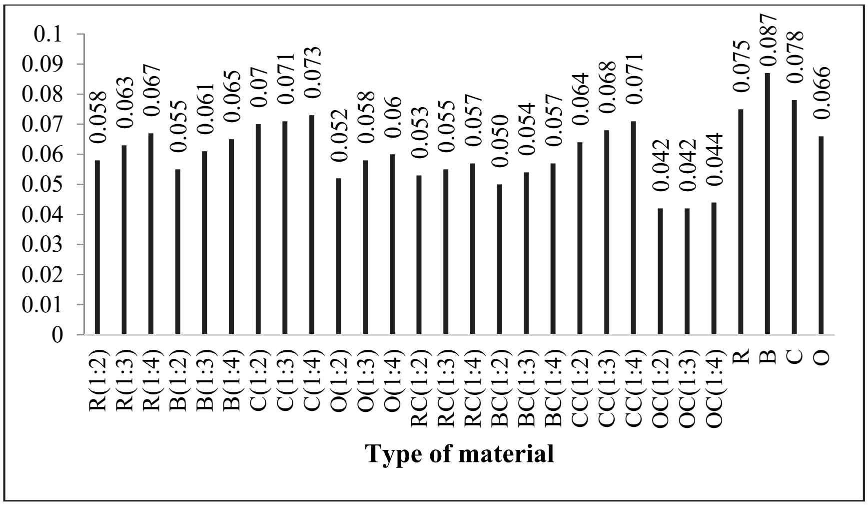

Fig. 7. Thermal conductivity of bio-based insulation materials (W/mK)

Table 4. Thermal conductivity of agricultural waste materials

Material	*Density (kg/m³)*	*Thermal conductivity (W/m K)*	*Reference*
Cotton stalk fibre	150-450	0.0585-0.0815	Zhou et al. (2010)
Particleboard from a mixture of durian peel and coconut coir	311-611	0.0728-0.1117	Khedari et al. (2004)
Kenaf binderless board	150-200	0.051-0.058	Xu et al. (2004)
Bagasse	625-740	0.04160-0.05784	Manohar (2012)
Date palm	753	0.15-0.17	Chikhi et al. (2013)
Durian peel fibre with latex	149-169	0.026-0.041	Jintakosol and Kumfu (2012)
Water hyacinth fibre with latex	465-646	0.025-0.031	Jaktorn and Jiajitsawat (2014)
Banana-waste plastic	1.049-1.102	0.334-0.408	Parkash (2015)
Rock wool	N/A	0.040	Abdou and Boudaiwi (2013)
Mineral wool	N/A	0.036	Abdou and Boudaiwi (2013)
Fibre glass	N/A	0.035	Abdou and Boudaiwi (2013)

3.2. Life cycle assessment results

Life cycle assessment of fibre preparation

LCA of fibre preparation was determined (Table 5) with the results of IPCC, expressed in GWP (Table 6) and Eco-indicator 99 (Table 7). The functional unit was set as 1 kg of prepared fibre. Results showed that oil palm fibre caused the lowest global warming impact while rice straw gave the highest. GWP throughout the life cycle of 1 kg prepared oil palm fibre was one-sixth of 1 kg rice straw fibre, nearly one-third of bagasse and about half of coconut coir.

Preparation of 1 kg of rice straw fibre required more than 3.5 times the electricity required for coconut coir and also quadruple NaOH solution due to the different proportions of the acquired fibres. The main contributions towards global warming were electricity consumption during preparation and reaction time with NaOH solution approximately 84% and 15% for every fibre type (Table 6). Regarding Eco-indicator 99, the main contribution was from use of NaOH solution and electricity in relatively close proportions with combined percentage accounting for 90% (Table 7).

Table 5. Life cycle impact assessment results

Type of fibre	*Global warming potential ($kgCO_2eq$/f.u.)*	*Eco-indicator 99 results (mPt/f.u.)*
Rice straw	110.0	1666.4
Bagasse	47.7	699.7
Coconut coir	31.9	488.6
Oil palm fibre	17.8	265.6

Life cycle assessment of bio-based insulation material

Environmental impacts of bio-based insulation materials were calculated for fibres formed by hot-pressing, using concentrated latex and mixed concentrated latex-chemicals as binder. The GWP of the insulation materials is shown in Table 8 with Eco-indicator 99 in Table 9. In terms of global warming, the same functional unit (R-value) for hot-pressing caused higher GWP than forming with a binder. Using hot-pressing, fibre from coconut coir has the least GWP (12.21 $kgCO_2eq$) while rice straw had the highest (60.69 $kgCO_2eq$). For binder consideration, OC(1:2) showed the lowest GWP (3.14 $kgCO_2eq$) and R(1:4) had the highest GWP (35.12 $kgCO_2eq$).

Reducing the mixture added to the binder such as OC(1:2) lowered GWP. The opposite result was realized when the mixture was high, such as OC(1:4). Results also revealed that most environmental impacts were caused during fibre preparation and contributions varied between 36.2% (OC(1:4)) to 88.8% (R), while those caused during the forming process were between 10.8% (R) to 60.8% (O(1:3)) and the impact from waste disposal was less than 3.3%. This can be explained by the use of electricity and NaOH solution during the preparation as mentioned earlier and electricity consumption for heat treatment during the forming process. For O(1:2), electricity consumption accounted for 57% of the impacts, followed by fibre extraction at 42% with binder impact at less than 1%. Similarly for OC(1:2), the main contribution factor was electricity at of 56%, followed by fibre extraction at 42% and binder less than 2% (Table 10). Electricity and chemicals were only partially shown during the forming process and quantities used during fibre extraction were already included in fibre preparation.

Likewise, the results of Eco-indicator 99 were similar to global warming impact mainly caused by electricity consumption during fibre preparation and heat treatment in the insulation process. Nonetheless, when considered contribution-wise, samples O(1:2) and OC(1:2) (Table 11) indicated that the main contributions were from fibre extraction and electricity consumption. Binder in OC(1:2) caused an 8.6% impact, while binder in O(1:2) resulted in less than 1% contribution.

Table 6. GWP contribution analysis results of each fibre type, using IPCC method (based on their own impact)

	Type of Fibre			
	Rice straw	***Bagasse***	***Coconut coir***	***Oil palm fiber***
Agricultural wastes	0.7%	0.3%	1.3%	0.5%
Electricity	83.8%	84.6%	84.7%	83.9%
Tab water	< 0.1%	< 0.1%	< 0.1%	< 0.1%
NaOH	15.5%	15.0%	13.9%	15.5%
Wastewater	< 0.1%	< 0.1%	< 0.1%	< 0.1%

Table 7. Single score contribution analysis results of each fibre type, using Eco-indicator 99 method (based on their own impact)

	Type of Fibre			
	Rice straw	***Baggasse***	***Coconut coir***	***Oil palm fiber***
Agricultural wastes	2.8%	0.7%	8.8%	1.4%
Electricity	43.9%	45.9%	43.9%	44.6%
Tab water	< 0.1%	< 0.1%	< 0.1%	< 0.1%
NaOH	52.8%	52.9%	46.9%	53.6%
Wastewater	0.4%	0.4%	0.4%	0.4%

Table 8. Global warming potential for each preparation sub-stage of specimens per functional unit

Material	***Life cycle stages (per f.u.)***			
	Fibre preparation (%contribution)	***Insulation process (%contribution)***	***Disposal (%contribution)***	***Total (kg CO_2eq)***
R	88.8	10.8	0.4	60.7
B	84.6	14.5	0.9	45.7
C	76.3	22.5	1.2	12.2
O	70.6	27.4	2.0	24.0
R (1:2)	59.9	39.6	0.4	20.8
R (1:3)	59.4	40.2	0.5	30.2
R (1:4)	58.9	40.5	0.6	35.1
B (1:2)	54.7	44.2	1.0	9.1
B (1:3)	54.4	44.2	1.3	9.9
B (1:4)	54.3	44.2	1.5	11.4
C (1:2)	42.0	56.9	1.2	5.3
C (1:3)	41.3	57.3	1.5	6.1
C (1:4)	41.1	57.1	1.8	6.1
O (1:2)	37.7	60.3	1.9	5.6
O (1:3)	36.9	60.8	2.3	6.5
O (1:4)	37.0	60.2	2.7	7.7 4
RC (1:2)	56.1	43.4	0.6	14.0
RC (1:3)	55.3	44.0	0.8	12.6
RC (1:4)	55.4	43.7	0.9	13.8
BC (1:2)	54.4	44.5	1.2	6.2
BC (1:3)	54.7	43.8	1.5	7.2
BC (1:4)	53.0	45.2	1.8	8.1
CC (1:2)	41.5	57.2	1.3	6.8

CC (1:3)	41.6	56.7	1.7	7.2
CC (1:4)	40.6	57.3	2.1	7.8
OC (1:2)	37.4	60.5	2.2	3.1
OC (1:3)	37.0	60.2	2.8	3.5
OC (1:4)	36.2	60.5	3.3	3.6

Table 9. Eco-indicator 99 results for each sub-stage of specimens per functional unit

Material	***Life cycle stages (per f.u.)***			
	Fibre preparation (%contribution)	***Insulation process (%contribution)***	***Disposal (%contribution)***	***Total impacts (mPt)***
R	93.2	5.9	0.9	876.1
B	89.6	8.3	2.1	632.2
C	84.3	12.9	2.8	169.3
O	78.9	16.3	4.8	321.1
R (1:2)	73.3	25.5	1.1	257.2
R (1:3)	72.7	25.9	1.3	373.4
R (1:4)	72.2	26.3	1.6	433.8
B (1:2)	67.4	29.8	2.8	108.1
B (1:3)	66.7	29.7	3.6	117.9
B (1:4)	66.3	29.7	4.0	137.1
C (1:2)	56.6	40.0	3.3	60.3
C (1:3)	55.5	40.3	4.1	69.0
C (1:4)	55.0	40.2	4.9	69.5
O (1:2)	50.9	43.7	5.4	62.1
O (1:3)	49.4	44.0	6.6	72.9
O (1:4)	49.1	43.3	7.5	87.3
RC (1:2)	67.8	30.7	1.5	174.7
RC (1:3)	66.1	32.1	1.9	159.4
RC (1:4)	64.9	32.8	2.3	178.3
BC (1:2)	62.5	34.6	2.9	78.5
BC (1:3)	60.3	36.2	3.5	95.9
BC (1:4)	56.9	39.0	4.1	110.6
CC (1:2)	51.6	45.0	3.4	83.6
CC (1:3)	49.4	46.5	4.1	93.5
CC (1:4)	46.6	48.5	4.9	104.4
OC (1:2)	44.0	50.6	5.4	39.9
OC (1:3)	40.7	52.9	6.4	47.9
OC (1:4)	37.6	55.1	7.2	51.1

Table 10. Contribution of GWP for O1:2 and OC1:2

	Type of thermal insulator	
	O1:2	***OC1:2***
Fiber preparation	42.0%	41.5%
Chemical binder	0.2%	0.7%
Electricity	56.6%	56.5%
Disposal	1.2%	1.3%

Table 11. Contribution of Eco-indicator 99 for O1:2 and OC1:2

	Type of thermal insulator	
	O1:2	***OC1:2***
Fiber preparation	56.6%	51.6%
Chemical binder	0.5%	8.6%
Electricity	39.6%	36.4%
Disposal	3.3%	3.4%

3.3. Eco-efficiency

Fig. 8 indicated the sustainable performance indicator of selected thermal materials which were calculated by EE. As EE indicator in this case study was defined as thermal resistance per GWP, the higher value, the better performance per unit environment load. The EE of the insulation pad appeared close to the upper right corner of the chart, reflected high EE, while lower left were low. The conventional thermal insulators including EPS and PUR presented the best performance among studied thermal materials which had 0.31 and 0.30, respectively. However among 31 thermal insulators, OC(1:2) was found to have the third highest EE at 0.23, better than XPS and followed by OC(1:3) with EE at 0.19, equal to XPS, while R had the lowest EE at 0.001. This results presented that oil palm fibre with concentrate latex-chemical mixed as a binder has the potential to develop into an environmental friendly product in term of global warming impact. The reason why insulator made by oil palm fibre material presented the best performances because the impact of global warming is lower than others (see Table 8), meanwhile thermal resistant performance is better (see Fig. 7). Furthermore, all insulators of present work were on the same slope (close to slope = 1, except for O and C which plotted almost on slope = 1). This imply that, even EE of those product were different, but ratio of performance/environmental value were almost the same. Performance and environmental value of those product increase or decrease with the same proportion. However EE of product C was quite equal to R(1:2), but high EE of C product was because of high performance, rather than low environmental impact. Comparing between commercial product XPS and OC(1:3), which had similar EE, OC(1:3) product seem to show higher environmental aspect.

3.4. Sensitivity analysis

Allocation of raw fibres

According to the base scenario, environmental burdens were allocated to the raw fibres. Raw straw is agricultural residue from rice cultivation, bagasse is waste from sugar production, coconut coir is waste from coconut juice production and oil palm fibre is waste from palm oil production. The base scenario allocated wastes. For instance, oil palm fibre sold as raw material for fuel (Silalertruksa and Gheewala, 2012) and bagasse was used as fuel for electricity generation (Mashoko et al., 2013). However, agricultural wastes cannot be allocated. For example, rice straw could be used as animal bedding or for energy generation, but it was not considered as an environmental burden associated with rice cultivation (Fusi et al., 2014) due to its negligible market value (Blengini and Busto, 2009). Thus, agricultural waste allocation was ignored as it presented no burden on the environment. Table 12 indicates the minimal effect of the specimens on GWP at around 1% of the total.

Transportation of raw fibre

The results in the base scenario were not determined for fibre transportation to the laboratory as the main study objective was to compare the material type and forming process of each specimen. However, to make the assessment more complete, transportation of raw fibre was taken into consideration. Distance from the laboratory was determined by the nearest cultivation areas that gave the highest volume of each raw fibre type. All four types of raw fibre were produced within 200 km from the laboratory. Moreover, the distance to the disposal area for landfill. Carried by a 4-wheeld pick-up truck, was assumed to be in the range of 40 km. Table 12 indicates that fibre transportation to the laboratory, as well as to the disposal area, caused minimal change in GWP of the specimens and accounted for less than 1%.

Emission factors of chemical binder ingredients

There was no life cycle inventory for some of the chemicals used in the concentrated latex mixture including potassium laurate, tetramethy thiuram disulphide and methyl cellulose. In the base case, other similar chemicals were used instead. However, here an assumption was made on the change in GWP result if the emission factors of the chemical ingredients in the chemical binder were changed by 50%. Table 12 suggests that the change of emission factors by 50% would not cause any variation in GWP as the %change was less than 1% (no change also for OC(1:2)). However, fibre types C and C(1:2) were not formed using chemical binder.

3.5 Limitation of the study and opportunities for improvement

Using data from lab-scale such as electricity consumption, it can make the value different from the actual production in the industry. Moreover, installation and disposal phases should be considered. Based on the results of environmental impacts, three main contributions of GWP impact were electricity consumption, use of NaOH solution during fibre extraction and heat treatment process. However, another alternative to chemical methods for fibre extraction is steam exploded treatment. Previous reports indicated that steam treatment together with alkali treatment decreased hemicellulose and lignin in raw fibre (Zhang et al., 2008; Deepa et al., 2011). Moreover, the steam explosion process mitigated negative environmental impacts in some categories including eutrophication and toxicity but was 12% higher in terms of GWP when compared with chemical treatments (Boonterm et al., 2016). Nonetheless, steam treatment can effectively reduce loss of cellulose by 7–8% compared to chemical methods (Rocha et al., 2015). Therefore, opportunities exist to develop efficient thermal insulation materials that are more environmentally friendly, particularly following chemical-free production processes and cellulose loss prevention during fibre preparation.

Table 12. Sensitivity analysis

Fire type	***Base scenario (kg CO_2eq/f.u.)***	***% Change***		
		Scenario 1	***Scenario 2***	***Scenario 3***
C	12.21	1%	< 1%	0%
C(1:2)	5.31	1%	< 1%	0%
OC(1:2)	3.14	< 1%	< 1%	< 1%

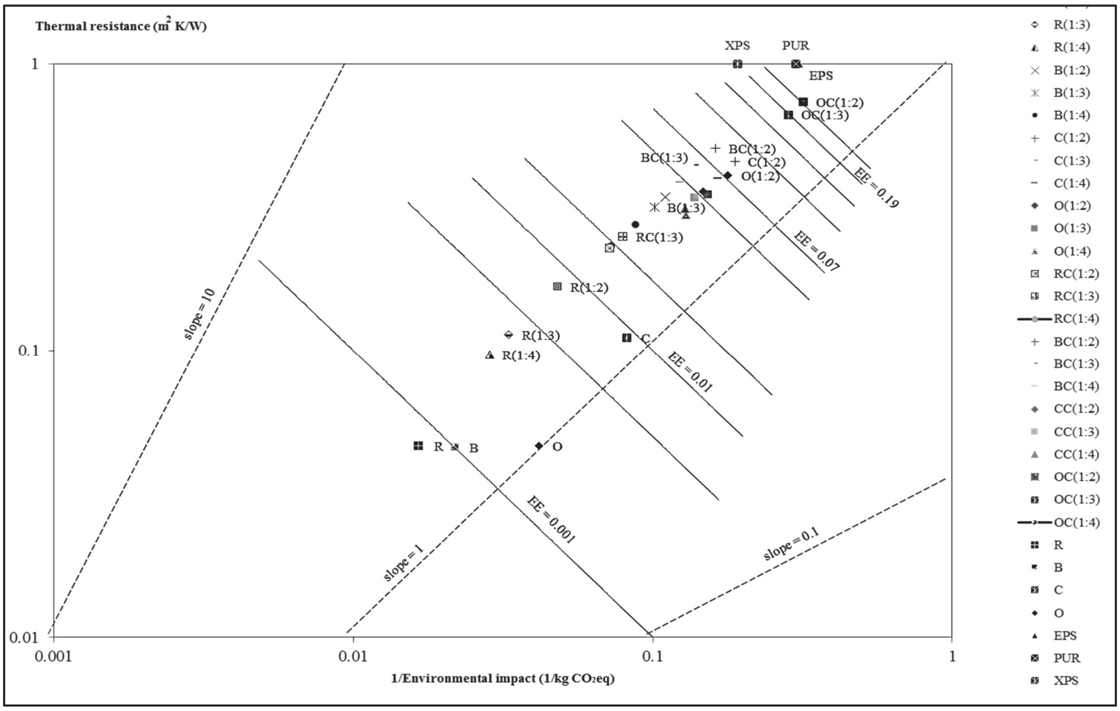

Fig. 8. Relationship between thermal resistance and inverse of environmental impact.

4. Conclusions

Rice straw, bagasse, coconut coir and oil palm fibre were formed into thermal insulation materials by the two different methods of hot-pressing and using latex as a binder. These fibres possessed good workable qualities for thermal insulation materials. Their thermal conductivities ranged between 0.042–0.087 W/mK within the standard and also low values close to commercial thermal insulators rock wool and fibre glass.

However, some improvements were required in fire resistance for construction purposes. From the environmental aspect, the hot-pressing formation technique caused greater negative impacts compared to using latex binder.

LCA results indicated that insulation material made from oil palm fibre and formed by a latex-chemical mixture binder caused the least environmental impacts with ratio of fibre to binder set at 1:2 (OC(1:2)) and eco-efficiency close to EPS, PUR and XPS as conventional insulators. The main contributing environmental impact factors were electricity consumption and use of chemical solutions, including heat treatment to dry the insulation pads during the production process.

Sourcing a more environmentally friendly alternative for fibre preparation rather than by using chemical treatments will provide an opportunity to reduce the global warming potential impact and might be other impact categories.

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