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Life Cycle Assessment of Natural Fiber-Based Insulator Corrugated Paper Box to Identify Eco-Design Strategies

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Abstract. This study explored the potential use of natural fibers as alternative insulate lining in a corrugated paper box for fresh asparagus transportation packaging. Life Cycle Assessment (LCA) was used to evaluate the potential environmental impacts of a natural fiber-based insulation prototype that could help identify the eco-design strategies. The environmental performances of the prototype were evaluated and compared with a corrugated paper box, with forced air cooling before shipment, and a corrugated paper box lined with polyethylene foam and filled with dry ice. The system boundary was the whole life cycle of products. The functional unit on which the comparison was defined as a corrugated paper box (1,100 cm×1,100 cm×1,000 cm) with a load of 300 kg of fresh asparagus for the transportation to a specific oversea destination by air fleet. Data collection was from primary data (i.e. natural fiber-based insulator production) and the background data were sourced from the national life cycle inventory databases (i.e. electricity, water, polyethylene foam), supplemented by international databases (i.e. chemical production, transportation) and literature review (i.e. corrugated paper box production). The LCA results indicated that, for the natural fiber-based insulation production, the highest impact on global warming was associated with the use of electricity by the fiber-drying oven; moreover, the use of sodium hydroxide, for the fiber extraction, caused a significant impact on eco-toxicity. The strategies for eco-design to improve the environmental performances of the natural-fiber insulation could be achieved by avoiding the chemical-extraction process and increasing the energy efficiency of the fiber-drying process. The alternative application of mechanically-steam explosion of natural fibers, instead of the chemical extraction method, could potentially reduce the environmental impact on freshwater eutrophication 83%, human toxicity 74% and terrestrial eco-toxicity 76%. By using a drying technique with higher energy efficiency, it could potentially reduce the use of electricity by approximately 50%. The environmental impacts could potentially be reduced on climate change 29%, terrestrial acidification 25% and freshwater eco-toxicity 15%, respectively.

Keywords: Corrugated box, eco-design, insulator, life cycle assessment, natural fiber.

1. Introduction

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Packaging is essential for a product protection during storage and transportation from producers to consumers. At present, an expanded-polystyrene (EPS) foam box is typically used as a packaging of fresh fruits and vegetables for import/export air-fleet shipping. There is a great concern over the increasing use of EPS foam packaging, a non-degradable, non-sustainable and heavily-polluting synthetic polymer that can hazardously impact the environment. Therefore, many countries have prohibited the use of polystyrene foam for oversea shipment [1]. As a consequence, a bio-degradable packaging product, which has the insulation capacity equivalent to a polystyrene box, has been developed extensively. The previous study investigated the feasibility of using chemically-extracted rice straw fibers as a thermal insulation material [2]. The extracted fibers were formed into a thermal insulation pad by a spray lay-up method using natural rubber as a binder; the natural-fiber insulation was consequently lined in a Kraft paper box packaging. The results showed that the natural fiber-based insulator lined box could potentially be used as an alternative insulation in packaging industries [2]. This has led to the objective of this study is to development of a prototype product as an alternative transport packaging and investigates the environmental performances to identify eco-design strategies.

2. Methodology

Life Cycle Assessment (LCA) method according to the ISO14040 [3] was used to evaluate the environmental performances of a corrugated paper box lined with a natural fiber-based insulation for comparison with other commercial insulation materials. The scope of the analysis was on the basis of the "cradle-to-grave" approach as illustrated in Figure 1. The functional unit was set as a corrugated paper box (1,100 cm×1,100 cm×1,000 cm) using for packaging transportation to a specific oversea destination by air fleet. The weight of natural fiber-based insulator corrugated paper box was 27.85 kg per box that could be used to pack 300 kg of fresh asparagus; the required temperature limit inside the packaging must be under 4 ^{o} C at the packaging factory and under 12 ^{o} C once the package reached the destination country (assuming Australia in this case).

The natural fiber-based insulation processing can be divided into 3 steps: natural fiber preparation, natural rubber preparation and forming an insulation sheet. In this study, rice straws were used as raw materials for natural fibers. First, rice straws were cut into small pieces and treated with 15% sodium hydroxide for 30 minutes to extract natural fibers; then, they were dried in an oven at 80 ℃ for 6 h. Later on, an insulation sheet was formed by laying up a layer of rice straw fibers and spraying the layer with natural rubber latex as binder; consequently, the layer was dried in an oven at 100 ℃ for 2 h. Finally, the natural fiber-based insulation sheet was lined in a corrugated paper box. The associated inputs and outputs of natural fiber-based insulation made from rice straw were then collected, based on the primary data. The background data were sourced from Thailand national LCI database (i.e. water, polyethylene foam), international databases mainly from EcoInvent, version 2.2. (i.e. chemical, transportation) and literature review (i.e. corrugated box production, electricity). The Recipe midpoint (H) method was used to summarize and recalculate the resources use and emissions to the environment into the environmental impact potentials. In the study, environmental impact categories of interest included climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), human toxicity (HT), terrestrial eco-toxicity (TET), marine eco-toxicity (MET) and freshwater eco-toxicity (FET).

The environmental performances of using a natural fiber-based insulator corrugated paper box, namely Scenario 1, was compared with the current packaging practices: corrugated paper box with forced air cooling, namely Scenario 2, and the corrugated paper box lined with polyethylene foam and filled with dry ice, namely Scenario 3. It is worth mentioning that the weight of the corrugated paper box with forced air cooling (scenario 2) is 7.79 kg and the weight of the corrugated paper box lined with polyethylene foam and filled with dry ice (scenario 3) is 13.8 kg. After use, the corrugated paper box was partly landfilled (22%) and recycled (78%), whereas the natural fiber-based insulator was naturally decomposed 100%; the polyethylene foam was landfilled 100%.

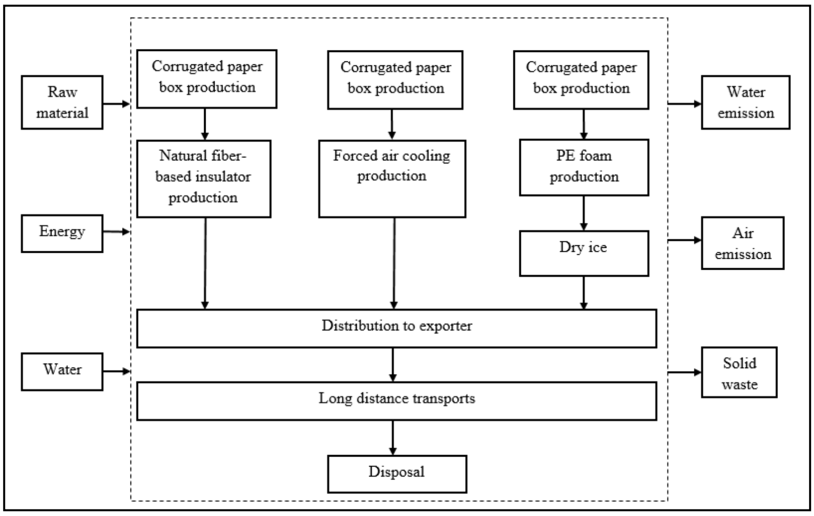

Fig.1: System boundary of LCA study

3. Results and Discussion

The inventory data of 1 kg natural-fiber based insulator production was showed in Table 1. Furthermore, the comparative environmental profiles of different scenarios were showed in Figure 2. The use of natural fiber-based insulator corrugated paper box (scenario 1) had the highest magnitudes of all impacts followed by the use of corrugated paper box with polyethylene foam and dry ice (scenario 3) and the corrugated paper box with using forced air cooling (scenario 2).

Table 1: Inventory data of 1 kg natural fiber-based insulator

Resource	Amount	Unit	Product	Amount	Unit
Rice straw	2.48	kg	Insulation	1	kg
Sodium hydroxide	7.4	kg	Waste		
Water	396	L	Waste water	390	L
Natural rubber latex	0.35	kg	Fiber waste	0.44	kg
Electricity	37	kWh			

The environmental impact potentials of scenario 1 were higher than scenario 2 on climate change by 21%, terrestrial acidification 21%, freshwater eutrophication 22% and human toxicity 31%. The environmental impacts of scenario 1 were higher than those of scenario 3 on climate change by 12%, terrestrial acidification 12% and human toxicity 25%. Although the corrugated paper box with using forced air cooling was the best on the environment aspect but its thermal insulation property was the worst. However, the corrugated paper box with using forced air cooling is still used normally in real situations. For the corrugated paper box with polyethylene foam and dry ice performed the best on the thermal insulation aspect. However, for short transportation duration, they could potentially be used and met the temperature control requirement. The environmental impact potentials of the corrugated paper box contributed to climate change 7% and terrestrial acidification 6%. The main contributors were from the paperboard production that used large amount of electricity in a drying stage. The results were similar to the previous study that the sources of global warming were primary due to CO_2 emission from steam and electricity production based on fossil fuel (coal, oil and natural gas) [4]. The important sources of NO_x and SO_2 emission mostly were from steam and electricity production. It was then suggested that cleaner technology could be applied for corrugated paper box production, e.g. electricity could be reduced by 40 to 60 % and it could reduce the impacts on global warming about 20% and acidification 10% [4].

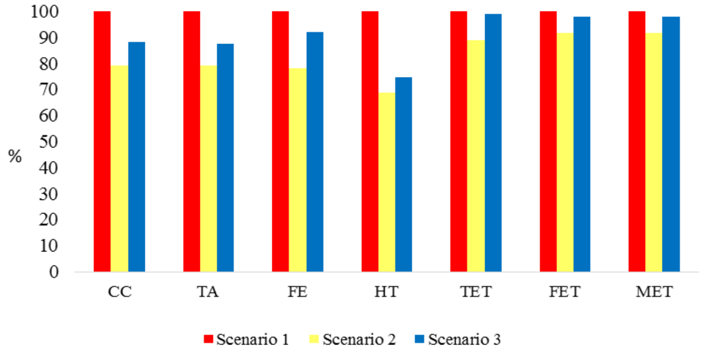

Fig. 2: Comparison of environmental profiles of corrugated paper boxes with different scenarios

The environmental profiles of natural fiber-based insulation, as shown in Fig. 3, indicated that the main contributors were from the use of electricity and the use of sodium hydroxide. The use of electricity, mostly expended during drying stage, contributed to climate change, terrestrial acidification and freshwater eco-toxicity 62%, 55% and 32% respectively. The use of sodium hydroxide in the natural fiber preparation contributed to stage human toxicity, terrestrial eco-toxicity and marine eco-toxicity 69%, 40% and 39% respectively.

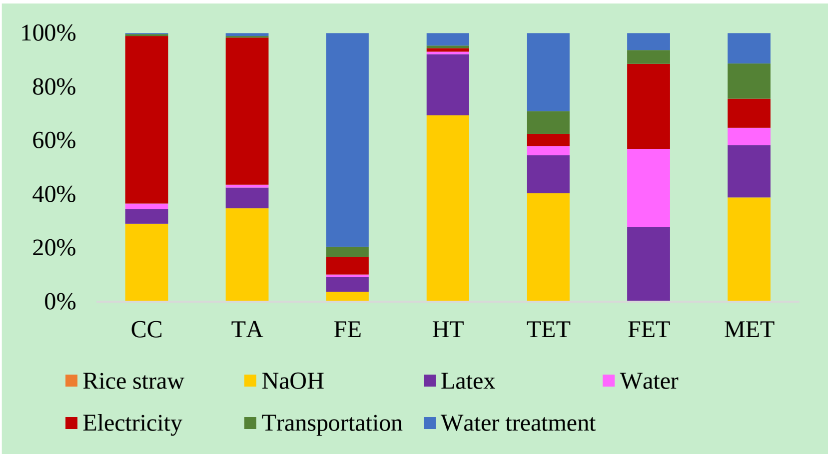

Fig. 3: Environmental profile of natural fiber-based insulation production process

It is evident that the major environmental impact potentials of the natural fiber-based insulation were due to the use of sodium hydroxide and poor energy efficiency of the drying processes. As a result, we investigated the feasibility of using a mechanical steam explosion as an alternative natural-fiber production technique to avoid the use of the NaOH chemical extraction process. The steam explosion process steamed raw rice straws under high pressure and temperature for 5-10 minutes, and suddenly released the pressure resulting in depolymerization of the lignin components and defibrillization [5]. Another previous study also suggested that the pre-treatment with steam explosion and xylanase resulted in 23% reduction of bleaching chemical [6]. Yet, it should be noted that the steam explosion option increased the use of electricity from 37 kWh to 63 kWh per 1 kg natural fiber-based insulator as compared to the NaOH chemical extraction. The environmental-impact results of using the steam explosion for fiber treatment (Option 1) was showed in Table 2; the use of the steam explosion instead of the chemical process could potentially reduce the environmental impacts on freshwater eutrophication by 83%, terrestrial eco-toxicity 76% and human toxicity 74%. However, the climate change and terrestrial acidification potentials were increased 12% and 1% with the use of the steam explosion due to its higher electricity consumption. As a result, the use of new drying technology with higher energy efficiency (e.g. using infrared or microwave drying method instead of oven), namely Option 2, was proposed and evaluated. By increasing the energy efficiency during the drying process, the use of electricity could be reduced by approximately 50% in the drying stage. The environmental-impact results of Option 2, as shown in Table 2, showed the reductions in all environmental impacts, as compared to the NaOH fiber treatment method, especially for climate change 29%, terrestrial acidification 25% and freshwater eco-toxicity 15%.

Table 2: Environmental performances and potential reduction of the environmental impacts with the use of the mechanical steam explosion for fiber treatment (Option 1) and the use of high energy-efficient drying process (Option 2), as compared to the natural fiber-based insulation processed by the NaOH chemical treatment technique (Prototype)

Impact category	Unit	Prototype	Option 1	%Reduction	Option 2	%Reduction
Climate change	kg CO2 eq	36.1474	40.6394	-12	25.7859	29
Terrestrial acidification	kg SO2 eq	0.1384	0.1402	-1	0.1036	25
Freshwater eutrophication	kg P eq	0.0006	0.0001	83	0.0006	3
Human toxicity	kg 1,4-DB eq	0.9556	0.2453	74	0.9499	1
Terrestrial eco-toxicity	kg 1,4-DB eq	0.0003	0.0001	76	0.0003	2
Freshwater eco-toxicity	kg 1,4-DB eq	0.0016	0.0014	11	0.0014	15
Marine eco-toxicity	kg 1,4-DB eq	0.0020	0.0008	57	0.0019	5

4. Conclusion

The environmental profiles of the natural fiber-based insulator corrugated paper box performed poorer than the current packaging practices using the corrugated paper box with force air cooling or the corrugated paper box lined with polyethylene foam and filled dry ice. The LCA results indicated that the highest impact on global warming was associated with the use of electricity and the use of sodium hydroxide that caused a significant impact on eco-toxicity. The environmental impacts could potentially be reduced with the improvement options by using the steam explosion method instead of the use of sodium hydroxide and using a higher energy-efficient drying process. By avoiding the use of sodium hydroxide, it could potentially reduce the environmental impacts on freshwater eutrophication, human toxicity and terrestrial eco-toxicity. Better energy efficiency of the drying process could potentially reduce the environmental impacts on climate change, terrestrial acidification and freshwater eco-toxicity.

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