THESIS

LIFE CYCLE ASSESSMENT AND ECO-EFFICIENCY OF DIFFERENT RICEBERRY PRODUCTS TO MOVE TOWARDS SUSTAINABILITY

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Riceberry rice has been encouraged for high value-added products targeting the health and wellness niche markets via the Thailand 4.0 national policy. Life Cycle Assessment (LCA) and eco-efficiency were applied to various riceberry products as the analytical tools of environmental and economic performances to provide supporting information for policy decisions. The system boundary was set from cradle to grave. The unit of analysis was defined as the sold unit of the studied products, namely: 90 g of riceberry soap, 250 ml of riceberry hair conditioner, 35 g of riceberry porridge, and 50 g of riceberry snack bar. The foreground data associated with the production processing activities were collected from local manufacturers based on the annual production in 2019 and the associated background data were sourced from the national life cycle inventory databases and supplemented by international databases when necessary. The LCA results indicated that the raw material acquisition stage was the major hotspot. Based on these findings, improvement opportunities were focused on the rice farming stage by applying alternate wetting and drying (AWD) farming, modification of recipes, and re-designing of packaging. By using the riceberry rice applying AWD practice, the impact on global warming for all products could potentially reduce by 20-34%. Moreover, the eco-profile of riceberry soap could be improved by replacing coconut oil with palm kernel oil could potentially increase the eco-efficiency by 1-75%. For riceberry hair conditioner, focusing on the re-designing the packaging by recycled PET bottles could potentially increase the eco-efficiency by 8-105%. For riceberry porridge, the company also proposed to have a new recipe, by removing the celery and adding more mushrooms instead, and re-designing the packaging by paper cups which had the potential to increase the eco-efficiency value by 1-51%. For the riceberry snack bar, replacing the apricot and cashew nuts by peanuts and pineapple that offer similar flavors had the potential to increase the eco-efficiency value by 4-48%. The outcomes indicated that riceberry soap, riceberry hair conditioner, and riceberry snack bar should be promoted for further development towards the value-based economic system according to Thailand 4.0. This information was also very useful for guiding the private companies in the development of sustainable products as well as supporting information for policy makers to move towards sustainability.

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INTRODUCTION

Thailand has been a leading world rice producer. Rice is primarily grown and cultivated as a subsistence crop, and surplus is exported into the global market. In 2020, Thailand was the world's 6th largest rice producer and the world's second-largest exporter of rice with 21% of the market share the cultivation area covers about 45.2% of the agricultural area in the country, consisted of 4.3 million households rice farmers or 74.4% of total agricultural households (Sowcharoensuk, 2019; USDA, 2020). As for the major rice in the year 2019/2020, the average rice production capacity of Thailand was 31 Million tons which were consisted of colored rice about 19,500 tons. Riceberry rice had the proportion of 22% of colored rice, which accounted for 4,333 tons of riceberry rice (Department Of Agriculture Extension, 2021)

Aiming to improve the rice variety with high nutrition to respond to the consumer preferences riceberry rice, (*Oryza sativa*) a crossbreed of Jao Hom Nin (a local non-glutinous purple rice) and Khao Dawk Mali 105 (Hommali rice), was developed by the Rice Science Center, Kasetsart University, Thailand. The outcome is a dark purple rice, similar to the dark purple berries, with a slender shape. The texture is soft and chewy offering a unique aroma fragrant when cooked (Rice Science Center & Rice Gene Discoovery, 2015)

Positioning as a portion of healthy food, riceberry rice has received much attention in recent years and has excelled in premium markets and niche markets. Riceberry rice is enriched with anthocyanin, which normally rich in colored rice, and this offers the antioxidant property to consumers (Vanavichit, 2020), for example, beta carotene, gamma oryzanol, tocopherol, carotenoid, vitamin E, tannin, zinc, and folate (Sapantupong, 2019). Several studies have shown the benefits of riceberry rice which are linked to its high antioxidant contents and helps in reduces the risk of cancer (Prangthip *et al.*, 2013). Additionally, anthocyanins found in the pericarp of riceberry rice have the potential in lowering cholesterol in the blood vessels as well as enhancing the digestion and absorption of lipids in the blood system (Poosri *et al.*, 2019). The beneficial properties of riceberry rice have led to the research and development of making riceberry rice into high value-added products or use riceberry rice as an alternative raw material in Food products Such as substituting cow's milk or use as flour in bread products (Siam Commecial Bank, 2015). For instance, the benefits from fiber and vitamin E in riceberry rice are useful for replacing the milk in panna cotta to eliminate free radicals and the growth of cancer cells, which is also suitable for people who are allergic to cow's milk (Pakwan *et al.*, 2018). The beneficial properties from anthocyanin in riceberry rice was also applied in healthy jelly products to reduce the fat content from coconut milk by 50% (Chuaykarn *et al.*, 2016). Moreover, it also increased antioxidant and other nutrients beneficial to consumer health in riceberry flour comparing to normal rice (Chuaykran *et al.*, 2013)

Life Cycle Assessment (LCA) is an environmental analytical tool for assessing potential environmental impacts throughout a product's life cycle at all stages from raw material acquisition through the production process, use and consumption, end-of-life treatment, recycling, and final disposal, including transportation in each stage (ISO, 2006a, 2006b). The potential use of LCA is to assist in identifying opportunities to improve the environmental performances of products at various points in their life cycle. Moreover, the application of LCA also helps to promote and develop the sustainable design of products and processes, to reduce overall environmental impacts (Pepper *et al.*, 2011). Although its use is mainly associated with the estimation of the environmental impacts of products, some studies have also used LCA combined with Life Cycle Cost (LCC) or eco-efficiency for evaluating the sustainability of products and services in terms of economic and environmental performances *(Jirapornvaree et al.*, 2021; Settanni *et al.*, 2010)

LCA has been applied for many agricultural products. For example Yodkhum *et al.* (2017) applied LCA to calculate GHG emission arising from paddy rice and reported that 83% of GHG emission was directly emitted from rice fields during the rice cultivation, followed by land preparation (9%), harvesting (5%) and other stages, e.g., planting, cultivation, and transport of raw materials, (3%). Similarly, Zhang *et al.* (2017) reported that the main hotspot of GHG emission was from the rice cultivation stage. LCA was used to assess the environmental impacts of rice-based bread (Jensen *et al.*, 2014) and the results indicated that the raw material acquisition stage was the main hotspot causing 0.412 $kgCO_2e$ while that from the production process was only 0.279 $kgCO_2e$. Recanati *et al.* (2018) conducted the LCA study of chocolate bar and reported that the highest n environmental impacts occurred at the cocoa bean production (63% for the ODP (Ozone Depletion Potential), 92% for EU (Eutrophication Potential), and 99% for the AD (Acidification Potential); for the production process, the environmental impacts were from energy use during the processing of chocolate bar leading to the generation of 39% on the GW (Global Warming) and 49% for the CED (Cumulative Energy Demand). Therefore, the obtained results from many studies have suggested focusing on the hotspots relating to the raw material acquisition and the production processing stages for improvement.

Eco-efficiency assessment is a quantitative tool to evaluate the relation between life cycle environmental impacts of products system along with its products system value or economic performance (ISO, 2012). The potential uses of eco-efficiency are increasing product or service values, optimizing the usages of resources, and reducing environmental impacts (Sengupta *et al.*, 2015). In addition, eco-efficiency can be a useful tool for benchmarking between the products and the agricultural management system. Previous studies on the application of eco-efficiency in the agricultural sector indicated that organic farming had a higher eco-efficiency value due to lower impacts on the environment resulting from using natural fertilizers (Ho *et al.*, 2018; Müller *et al.*, 2015). Eco-efficiency was also used for comparing the advantages of rice production in different conditions under controlled irrigation and rain-fed conditions in both environmental and economic terms; the eco-efficiency value of the rain-fed farming system was equal to 4.04 baht/$kgCO_2e$ because of lower energy and resources consumption, while that of irrigated rice farming system in a dry and wet season was equal to 2.16 and 2.46 baht/kgCO_2e, respectively (Thanawong *et al.*, 2014).

Being a regional leader in rice production and rice exporting, Thailand has developed the national policy on sustainable agriculture especially for rice production (Department of Rice, 2012). Moreover, the country has launched the strategic policy on Thailand 4.0 aiming to develop the country into a value-based economy especially for rice to develop high-value-added rice products in order to increase the exporting revenue (Rawangsamrong, 2018). Several new processed products from riceberry rice have been developed in Thailand, such as riceberry snacks, bread, riceberry bran oil, riceberry milk, and cosmetics with high value-added such as soap, lipstick, and hand cream. At the same time, it was very well aware that consumers are interested in selecting food products by using nutritional level and environmental-friendliness criteria (Andersson K. *et al.*, 1994). To respond to the consumer preference and respond to the sustainability and Thailand 4.0 policy, this study was developed to evaluate the environmental impacts and economic performances of various riceberry products by using LCA and Eco-efficiency as the first attempt in Thailand. It was expected that the information gained from the LCA and Eco-efficiency study could be useful for supporting the private companies to improve the environmental profiles and economic performances of riceberry products and to provide policy recommendations on which processed riceberry products should be further developed and promoted for exporting countries to move towards sustainability.

OBJECTIVES

1. To assess the environmental and economic performances of processed products from riceberry rice by using Life Cycle Assessment and Eco-efficiency.

2. To provide decision supporting information to improve environmental and economic performances of riceberry products for private companies and to suggest which products should be further developed and promoted to move towards sustainability for policymakers.

LITERATURE REVIEW

1. Sustainability issues associated with the rice industry

1.1 Environmental dimension

The Thai rice industry is the most important source of employment, engaging 5,004,792 households of farmers, and the income of the country generating 130,584 million baht in 2019. However, there is a trade-off between using natural resources and generating adverse environmental impacts for that. For environmental sustainability issues, related to many problems such as climate change, land-use change, biodiversity loss, and environmental pollution. The sustainability issues in the rice industry related to the environment particularly in Thailand are summarized as follows:

1.1.1 Methane emission from rice fields

Agricultural activities are highlighted as one of the major sources of GHG emissions. Especially for rice, it was emphasized as the key contributor to emissions in several countries including Thailand. The GHG emission from rice fields mostly came from methane generated from the degradation of organic matter by micro-organisms in the soil and emitted directly from the gaps inside the rice stems during the rice cultivation especially in the rice flowering stage (Towprayoon *et al.*, 2003). The main factors affecting methane gas generation were related to the soil quality, the organic matter and the flooding system in the rice fields, flooding system in rice field leading to an anaerobic condition where sulphate and nitrate concentration in soil is low and occurs methanogenic fermentation, this reaction produce CH_4 and CO_2 emission according to the chemical reaction: $C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$ (Mer *et al.*, 2001). This process simply called the methanogenic process, the source of materials for all these reactions are the rice straws remaining after harvesting in the rice field, it can be decomposed and become the main source of methanogenic substrates (Denier van der Gon *et al.*, 2016; Naser *et al.*, 2007). As shown in **Figure 1**. Once the methane gas is produced from the methanogenic processes, it is now transported vertically to the atmosphere through three main pathways. These pathways include diffusion of dissolved methane that reaches the flooded waters, the emergence of bubbles triggered by soil fauna and crop management procedures, and finally plant transport by diffusion into the roots and conversion to gaseous methane in the cortex and aerenchyma and subsequent release of methane to the atmosphere through plant micropores (Wassmann *et al.*, 1993).

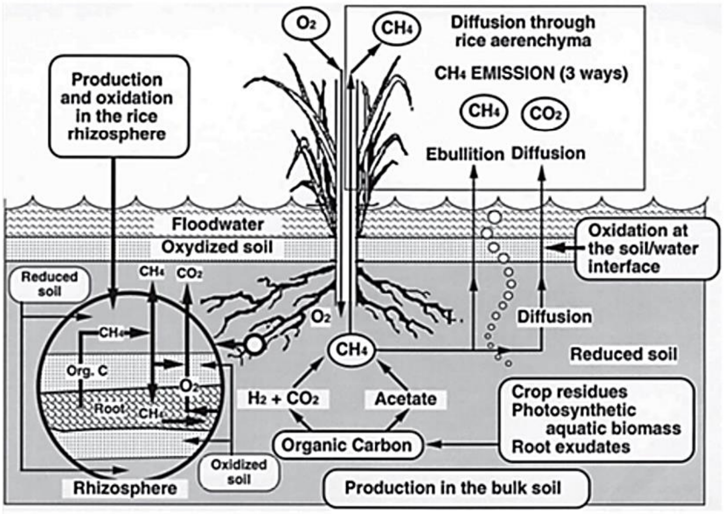

Figure 1 Methane gas formation in rice fields
Source: Vanichsan *et al.*, (2011)

1.1.2 Soil quality deterioration

A large number of chemical fertilizers and pesticides are used to ensure a high yield, which resulted in day by day of declining soil health, losing soil organic matter, decreasing soil fertility, and degraded soil structural conditions. Moreover, rice straw burning also resulted in losing soil nutrients and its quality along with the generation of GHG emissions such as the release of CO_2 emission from the ground to the atmosphere which is an important source of global warming. In addition, smoldering or burning also caused degrading soil physical and biological health (Singh, 1939). Therefore, rice farmers adding more fertilizers to have potential yields during the rice farming stage, finally faced with a higher cost of rice cultivation in the short term and lower soil quality and productivity in the long-term leading to sustainability issues (Bhatt *et al.*, 2016)

1.1.3 Environmental pollution

Management of rice stubble and rice straw is a major challenge for rice farmers. Some farmers still did the burning of rice straw/stubbles because this practice was an easy and quick method of disposing of all rice residues. However, this was the main negative impact causing air pollution to the atmosphere (Gupta *et al.*, 2004). The burning of residues is a major contributor to reduced air quality, human respiratory ailments, and the death of beneficial soil fauna and microorganisms (Ladha *et al.*, 2004). Moreover, the burning of rice straw was the source of CO_2 emission release from the ground to the atmosphere which is an important source of global warming (Junpen *et al.*, 2018)

1.1.4 Biodiversity loss

Biodiversity loss in rice fields is affected by using agrochemicals and pesticides. Agrochemicals (including pesticides and growth regulators) have damaged agricultural areas and the surrounding natural vegetation, aquatic environment, and wildlife, thus decreasing rice paddy biodiversity. It also destroys the biological refuge and wildlife habitats provided by paddy rice fields. Biodiversity loss also reduces the number of edible species traditionally harvested from rice fields, such as snails, prawns, crabs, large water bugs, fish, and frogs, which leads to the unsustainable development of the paddy field ecosystem (Luo *et al.*, 2014). However, organic rice farming was reported to help to conserve biodiversity (Linke *et al.*, 2014)

1.2 Economic dimension

For economic issues, the rice export market is highly competitive, and the pricing has been fluctuating. Revenue from rice exporting and trading varies depending on the type of rice, the demand of domestic and global markets, and increasing production costs.

1.2.1 Competitiveness in the rice industry

The competitiveness in the rice industry is a general issue for rice export countries. Although, at present Thailand is the world's 2nd largest rice exporter in the major rice year 2019/2020. However, the exporting market of Thai rice faced many competitions from other Asian countries such as China, India, Vietnam, Cambodia, and Myanmar. The production cost is the main issue related to the rice price competition for the export market. In Thailand, the way of production has changed. Farmers focus on growing rice for high productivity resulting in the soil condition deterioration and the poor quality of rice. In addition, most of the rice fields especially in the northeast region are the rainfed system that relies mostly on rainfall. All of these resulted in higher production costs than neighboring countries. Pisarnwanich (2012) reported that the average production cost was about 9,763 baht/rai with an average production capacity of 450 kg/rai. High production cost mostly came from the cost of chemical fertilizer, pesticides, and service providers. In contrast, the production costs of Asian countries (such as Vietnam and Myanmar) are estimated to be 50% lower than Thailand ranging from 4,070 - 7,121 baht/rai with an average production of about 900 kg/rai in Vietnam. The lower production costs in Vietnam was due to cheaper wages and using the family labor for rice production (Jiacheng, 2018). The lower production cost in other Asian countries additionally resulted in a price fluctuation forcing Thailand to reduce the export price to tackle the international competition. In this connection, the lower prices for export markets resulted in lower income for the rice farmers.

1.2.2 Fluctuation of rice production and global prices

The supply chain of rice is still a multi-agent system consisting of many actors, i.e., rice farmers, rice mills, retailers, processing factories, and wholesale. For this reason, there is a huge gap between the price of paddy rice and the price of milled rice at the rice mill and retail gates. On the other hand, consumers have to pay a high price when they buy rice from retailers. Furthermore, the strong syndication among the stakeholders of rice creates complex conditions which are also responsible for the instability of the price of rice (Rahman, 2019). Fair contribution of profit is not taking place. Farmers had pressure to deal with high production costs due to the high price of fertilizers, high cost of labor. In addition, the production capacity of rice in the world market, as well as pressure on both the country's structural problems, world market, and the demand of consumers also causing the rice price, has been suppressed and decreased.

1.3 Social dimension

For social issues, the labor shortage is the main sustainability issue of Thailand's rice and agricultural industry, with the increasing trend of rural laborers engaging in industrialized employment, significant changes have occurred to the income structure and production and management mode of the farming system. An increase in the age of the agricultural workforce has also occurred, resulting in a shortage of agricultural labor, creating concern regarding food production, food security, and sustainability of the rice industry (Li *et al.*, 2016)

1.3.1 Labor shortage

Rice production is labor-intensive, the rice farming activities in the past required labor-intensive start from land preparation, rice transplanting, farm management, and harvesting of paddy rice with manual practice without chemicals use. Therefore, Labor forces in agriculture, especially rice production in Thailand, are important in terms of food production base to ensure food security and renewable energy for the country. But it is interesting to find that agriculture, especially rice production, has always experienced a labor shortage, same as other business sectors. At present, the labor shortage problem in the agricultural sector tends to spread to more areas. The main cause of labor shortage was found that the aging of labor starting from 40 years has continued to rise, but the group workers aged around 15 -39 years are declining rapidly (Changkid, 2007). At present, 33% of rice farming households. There were heads of households older than 60 years old, and the average age of rice farmers is 56 years old, implying the direction towards an aging society in the Thai rice industry. The aging society in the rice industry resulted in the decline of labor supplied, the migration from rural to urban society of labor force is common because of rapid industrial growth (Napasintuwong, 2019). It can be concluded that the new generation of workers is less entering the agricultural sector. As a result, the average age of agricultural workers is higher. This will result in a decrease in production efficiency in the future. Due to labor health problems, and there is a limit to learning new technology and innovation for increasing production efficiency. All these caused rice farmers to rely on the hiring of service providers and more dependent on agricultural machines which resulted in higher production costs rice production. (Bhatt *et al.*, 2016). Therefore, the labor shortage is an emerging issue for Thai rice cultivation leading to sustainability issues.

2. Riceberry rice

2.1 Development of riceberry rice

Colored rice is generally known as unpolished rice that contains some pigments retaining from rice bran and pericarp that still retaining from removing only rice husk and outer layer after the milling process. It consists of varieties color shades such as dark red, purple, black-purple depends on the anthocyanin content in the rice seeds. In the past, colored rice has been used as a functional food for health-conscious people and niche markets. However, most consumers in Thailand and Southeast Asia regularly prefer aromatic and soft texture long grain rice (Custodio *et al.*, 2016). Therefore, the new variety of colored rice has been researched and developed. The renowned new Thai riceberry rice has been originating in Thailand. It was first developed in 2002 by Dr. Apichart Vanvichit and their research team from Rice Science Centre, Kasetsart University, Thailand. The objective for this new rice variety was to improve the varieties adjusting to consumer preferences on food selection and to increase the demand for colored rice consumption in the market. The research team was selected Jao Hom Nin rice from Kasetsart University as a father breed and Khao Dawk Mali 105 as a mother breed, after approximately 7 times research and analysis of the nutritional value and properties in riceberry rice. Finally, in 2005 the deep purple whole grain rice was discovered with the shape of slender seeds, softness, and contain high antioxidants rice called “Riceberry”. From the first day that riceberry rice was first enter the Thai rice market over 15 years ago, at present, Riceberry rice is positioned as a portion of healthy food and has excelled in premium markets and niche markets, gaining a high value-added (Vanavichit, 2020).

2.2 Riceberry characteristics

Riceberry rice is one of the colored rice species which is a high nutrition rice, the main characteristics of whole riceberry seed are dark purple rice, similar to the dark purple berries, and slender shape. The texture is soft, chewy, and has a unique aroma fragrant when cooked. riceberry rice was combined the beneficial properties between white rice and colored rice to become the most nutritious and rich in aroma. Riceberry rice seeds consist of 4 main important parts. The outermost layer of riceberry rice is rice husk, it has the function of protecting the rice seed, it consists of cellulose and hemicellulose with 90% of SiO_2. The second part is riceberry bran, this part is the layer of unpolished rice that covers the endosperm inside the riceberry seed, and it’s concentrated with many nutritional properties, with only a small fraction in its endosperm. This is true of all cereals, meaning that it is best to consume brown rice, rather than polished rice. Riceberry barn is a rich source of antioxidants such as anthocyanin, carotenoid, gamma oryzanol, and vitamin E. The main part of riceberry rice is Endosperm, in this part covers about 80% of the total weight of riceberry seeds.

The endosperm part is the rich source of carbohydrates and only a small fraction of other nutritional properties (Vanavichit, 2020). Finally, the most important part is the riceberry germ which is the small part inside the endosperm of the riceberry seed. This part of rice is a rich source of vitamins and minerals such as vitamin B, iron, and zinc. In addition, riceberry germ is the part that will grow into a rice plant.

The important nutrition properties and minerals in each part of the riceberry rice can be described as follows:

Vitamins B plays important roles in the operation system of the brain, nervous system, digestive system and prevent the beriberi (Ampro Health, 2017). Moreover, it also helps in maintaining good health and well-being as it has a direct impact on energy levels, healthy brain function, and cell metabolism, growth of red blood cells (Cronkleton, 2019)

Beta Carotene a pro-vitamin-A carotenoid, or a nutrient that the body readily converts into vitamin A. It’s a vital nutrient for vision supports and prevents eye diseases, plays a critical role in cell growth and in maintaining healthy organs like the heart, lungs, and kidneys (Ampro Health, 2017)

Gamma oryzanol is a substance that is taken out of rice bran oil. It is also found in wheat bran and some fruits and vegetables. The benefits are helping in lowering cholesterol levels in the blood vessel (Ampro Health, 2017)

Dietary fiber is helpful in blocking the absorption of fat and cholesterol. Reduce the risk of fat embolism, colon cancer, help in control blood sugar levels and reduce the risk of normalizes intestinal motility, and reduces the incidence of constipation (Chinasan., 2016)

Omega 3 Fatty acid is essential for infant brain and retina development. It can help prevent Alzheimer's disease and dementia in elderly people. (Suksombat, 2018). Moreover, Omega 3 has many powerful health benefits to promote brain health during Pregnancy. Consumption of enough omega-3s during pregnancy and early life is crucial for your child’s development. Supplementing is linked to higher intelligence and a lower risk of several diseases. (Hjalmarsdottir, 2018).

Tannins (commonly referred to as tannic acid) are water-soluble polyphenols that are present in many plant foods. It can help in the digestive system of the body. However, the major effect of tannins was not due to their inhibition on food consumption or digestion but rather the decreased efficiency in converting the absorbed nutrients to new body substances (Chung *et al.*, 1998). In addition, most research indicated that tannin has been shown to reduce diarrhea and can inhibit the growth of bacteria such as theogallin, gallic acid, and ellagic acid (Malay, 2018)

Iron is one of the reductions in anemia. It is used for hemoglobin and red blood cell formation. There are factors for the development and growth of the body, nervous system, and brain in the day of generation and working age (Sangsom, 2013)

Vitamin E can reduce oxidative stress, which is the cause of Alzheimer's disease and carcinogenesis (Kontush *et al.*, 2004). In addition, Vitamin E can inhibit cell cycle progression and inhibit cell proliferation in prostate, colon, and osteoblast cancers.

The characteristics and nutritional properties of riceberry are shown in **Table 1-2.**

Table 1 Riceberry rice characteristics

Riceberry rice characteristics	
Plant height	105-110 cm.
Days to maturity	130 days
Yield (kg/rais)	300-500 kg/rais
% Brown rice	76 %
% head rice	50 %
Rice length	Rice paddy 11 mm.
	Brown rice 7.5 mm.
	Rice pad 7.0 mm.

Source: Rice Science Center & Rice Gene Discoovery, 2015

Table 2 Nutritional properties

Riceberry rice Nutritional value per 100 g (3.5 oz)	
Nutrient	**Quantity**
Energy	390 kCal
Protein	8 g
Carbohydrate	80 g
Fat	4 g
Fiber	4 g
Vitamins	
Vitamins A	63 µg
Folate	48 µg
Vitamins E	0.68 mg
Minerals	
Iron	1.8 mg
Omega3	25.51 mg
Sodium	50 mg
Zinc	3.2 mg
Antioxidants	
Gamma- oryzanol	462 µg/g
Tannin	45 mg
Anthocyanin	45 mg
Lutein	45 µg
Water-Soluble Antioxidant	47.5 mg ascorbic acid equivalent
Oil-Soluble Antioxidant	33.4 mg Trolox equivalent

Source: Rice Science Center & Rice Gene Discoovery, 2015

2.3 Statistical data of riceberry rice production

According to the statistical data of riceberry rice production from major crops in the year 2017/2018-2020/2021, riceberry rice is cultivated in both irrigated and non-irrigation zones, while white rice is mostly grown in irrigated zones. Interestingly, riceberry rice requires less water to grow than other rice varieties. In addition, riceberry rice also sells at a higher price when compared to other rice species. riceberry rice cultivated in wet seasons shown in **(Table 3)**. For the wet season, the cultivation area is mostly found in non-irrigation zones. The average cultivation area in the non-irrigation zone is ranging from 2,865-7,210 rais with an average yield of 509-543 kg/rai and the average selling price of paddy riceberry rice was about 11-14 THB/kg. For the irrigation zone, the average cultivation area in the irrigation zone is ranging from 1,111-3,299 rai with an average yield of 551-670 kg/rai and the average selling price is the same as that produced from the non-irrigation zone.

Table 3 Riceberry rice production capacity for wet season during major rice year 2017/2018-2020/2021

		Major rice year			
		2017/2018	2018/2019	2019/2020	2020/2021
No. of households	Irrigation zone	128	164	106	132
	Non-irrigation zone	712	778	482	313
Cultivation area (rais)	Irrigation zone	1,495	3,299	1,111	1,224
	Non-irrigation zone	7,211	5,706	4,612	2,866
Total yield (kg)	Irrigation zone	934,830	1,818,300	602,814	800,353
	Non-irrigation zone	3,890,970	2,908,830	2,200,449	1,506,826
Average yield area (kg / rai)	Irrigation zone	625	551	565	670
	Non-irrigation zone	543	510	486	528
Average farmer selling price (THB / kg)		13.89	12.2	12.08	11.86

Source: Department of Agriculture Extension, 2021

As shown in **Table 4,** for the dry season, the cultivation area found in both irrigation and non-irrigation zones are similar. The average cultivation area in the non-irrigation zone is ranging from 521-1,850 rais with an average yield of 566-717 kg/rais and the average selling price of paddy ricebery rice was about 11-14 THB/kg. For the irrigation zone, the average cultivation area in the irrigation zone is ranging from 364-976 rais with an average yield of 500-763 kg/rai and the average selling price is the same as that produced from the non-irrigation zone.

Table 4 Riceberry rice production capacity for dry season during major rice year 2017/2018-2020/2021

		Major rice year			
		2017/2018	2018/2019	2019/2020	2020/2021
No. of households	Irrigation zone	25	54	42	77
	Non-irrigation zone	50	82	138	32
Cultivation area (rais)	Irrigation zone	643	848	364	976
	Non-irrigation zone	522	827	1850	119
Total yield (kg)	Irrigation zone	383,590	610,175	202,613	11,000
	Non-irrigation zone	322,675	453,757	1,327,055	19,360
Average yield area (kg / rai)	Irrigation zone	763	737	557	500
	Non-irrigation zone	619	567	717	645
Average farmer selling price (THB / kg)		11.6	10.7	11.16	13.98

Source: Department of Agriculture Extension, 2021

2.4 Riceberry rice cultivation area and production capacity

The average riceberry rice cultivation areas and production capacity of Thailand in the major rice year 2019/2020 can separate into wet and dry seasons as shown in **Table 5-6.**

For the wet season in the major rice year 2019/2020, the average cultivation area is covered 49 provinces with the total cultivation area 5,723 rais, in this number consisting of 588 households of rice farmers. The total production capacity is 2,803.0

tons with the yield per rai of 501.34 kg/rai and the average selling price of paddy riceberyy rice was about 12.08 THB/kg (Department Of Agriculture Extension, 2021)

Table 5 Riceberry rice farming area wet-season rice 2019/2020

Province	Number of households	Cultivation area (rais)	Total yield (kg)	Average yield area (kg / rai)	Average farmer selling price (THB / kg)
Total	588	5,722.50	2,803,263	501	12.08
Songkhla	9	45	0	-	0.00
Chiang Rai	39	515.25	344,400	668	10.76
Sukhothai	1	43	32,250	750	6.80
Uthai Thani	31	446.5	196,100	529	9.56
Phetchabun	8	50	31,200	624	18.42
Nakhon Pathom	2	20	800	40	8.00
Lopburi	28	357.5	162,100	453	11.77
Kamphaeng Phet	7	109	68,050	624	6.78
Chonburi	6	27	10,800	400	25.93
Nong Khai	1	6.5	2,300	354	12.00
Phitsanulok	54	1,022.75	811,650	794	10.99
Chaiyaphum	40	20	8,500	425	15.00
Nakhon Sawan	3	20	10,000	500	15.00
Chiang Mai	38	218	145,088	666	12.33
Nakhon Ratchasima	130	1,630	346,000	212	13.99
Samut Songkhram	3	18	10,800	600	7.50
Chachoengsao	11	121	48,300	400	16.46
Prachuapkhiri khan	2	20	11,000	550	15.00

Province	Number of households	Cultivation area (rais)	Total yield (kg)	Average yield area (kg / rai)	Average farmer selling price (THB / kg)
Narathiwat	4	8	3,200	400	100.00
Ang Thong	1	12	9,600	800	9.00
Phra Nakhon Si Ayutthaya	4	77	57,530	750	9.18
Chai Nat	2	30	15,000	500	20.00
Phayao	5	2	1,125	500	13.00
Phang Nga	3	8	3,840	480	60.00
Phichit	1	2	1,500	750	10.00
Phetchaburi	16	205	119,740	584	9.47
Lampang	100	300	150,000	500	17.00
Lamphun	4	28	12,620	701	10.39
Sakon Nakhon	1	4	1,400	350	15.00
Sa Kaeo	14	180	63,000	350	20.00
Saraburi	7	65	38,570	593	10.00
Nong Bua Lamphu	1	8	3,400	425	15.00
Uttaradit	12	104	83,400	800	11.00

Source: Department Of Agriculture Extension, 2021

For the dry season in the major rice year 2019/2020, the average cultivation area is covered in 8 provinces with the total cultivation area rais, in this number consisting of 180 households of rice farmers. The total production capacity is 1,529 tons with the yield per rai of 691.06 kg/rai and the average selling price of paddy riceberry rice was about 11.16 THB/kg. (Department Of Agriculture Extension, 2021)

Table 6 Riceberry rice farming area dry-season rice 2019/2020

Province	Number of households	Cultivation area (rais)	Total yield (kg)	Average yield area (kg/rai)	Average farmer selling price (THB / kg)
Total	180	2,214	1,529,668	691	11.16
Nakhon Sawan	9	493	310,455	630	12.00
Buriram	28	120	57,600	480	20.00
Prachuap Khiri Khan	0	0	0	-	0.00
Pattani	15	70	40,600	580	12.00
Phra Nakhon Si Ayutthaya	1	5	2,250	450	7.00
Samut Songkhram	3	64	41,763	650	9.08
Phatthalung	52	134	46,900	350	20.00
Phichit	1	13	6,500	500	10.00
Phitsanulok	60	1,200	960,000	800	10.00
Phetchaburi	7	66	42,000	636	8.54
Lampang	1	15	5,700	380	20.00
Lamphun	1	4	800	200	15.00
Sakon Nakhon	1	6	2,400	400	50.00
Sing Buri	1	11	3,100	276	10.00
Ang Thong	0	12	9,600	800	7.00

Source: Department Of Agriculture Extension, 2021

2.5 Riceberry rice farming

Riceberry rice has an average production cycle of about 130 days. The organic rice farming method is mostly applied for cultivation. This method relies on natural methods such as the use of natural fertilizer, compost, and water management to protect the damage of rice.

The first step of riceberry rice farming starts by making the crop calendar, then followed by the riceberry rice cultivation practices step by step.

2.5.1 Making the crop calendar

It is a very important step in deciding on when to start the crop. The crop calendar (e.g., a schedule of the rice-growing season, starting from land preparation, crop establishment, harvesting, drying, and storage) is recommended to be well planned with good preparation of all rice farming activities. The crop calendar is creating steps by steps:

The first step is determining the best date to plant, this information can be gathered from a farmer's local experience, agricultural advisors, and leading farmers in the district. Rice farmers also can be studied from Thailand's rice planting calendar, which indicates the optimal timing for each region and the growing season of Thailand. Moreover, climate change also. When considering the crop calendar climate change is a factor that should be taken into consideration as well. Climate change results in unstable rainfall and irrigation water each year and affects the changing of rice farming season.

Generally, there are two seasons of rice farming. The wet season or regular rice farming has the period during the rainy season (May – October). This season is only once a year. The dry season or off-season is rice farming during the irregular period, which requires less support from the light for flowering and relies on the irrigation system. The period starts from January and harvests in April, at the latest. It is common in areas with exceptional irrigation systems such as the central region. Cultivation takes approximately 130 days and can expect to produce up to 2-3 crops per year. The planting season may be adjusted as appropriate for each area, and the amount of water in each period, including climate change. Secondly, the growth period of riceberry rice from planting to harvest should be determined. The length of time from the establishment to harvest is known for each variety. For riceberry rice, it takes 130 days to cultivate. Therefore, farmers should mark or note on the calendar the date of planting and then when each other operation needs to be done (plowing, weeding, fertilizing, and harvesting). After the date and farming period has been set up, the next step is to determine the resource, raw materials for rice farming along with the labor and equipment that will be required at each step during the growing period to calculate the production cost of riceberry rice farming.

2.6 Riceberry rice cultivation practices

The riceberry rice cultivation practices is explained step by step, here.

2.6.1 Land preparation

Land preparation is the first step to ensure that the area of the rice field is ready for rice farming. The initial land preparation begins after the harvest period. Because it is more effective to control weed and soil quality. There are 3 steps for land preparation.

1st Plowing is the first plow along the length of the rice field to "till" or dig up, mixing and overturning the soil. When plowing, it helps to turn the soil surface from the lower soil so it can come up to touch the oxygen and destroy the weeds, or some plant diseases. The plowing will begin when the first rainy season in the new season. After plowing, the soil will be dried for about 1-2 weeks.

2nd Plowing or harrowing after drying the soil. This step helps to break the soil clods into smaller masses and incorporate plant residue.

3rd Leveling the rice field and adjusting the area of the rice field to be consistent for ease of control and to take care of the water level.

Figure 2 Rake process

2.6.2 Crop establishment

The two main practices of establishing rice plants are transplanting and direct seeding.

Transplanting is the most popular plant establishment technique across Asia. Pre-germinated seedlings are transferred from a seedbed to the wet field. It requires less seed and is an effective method to control weeds but requires more labor. Seedlings may be transplanted by either machine or hand.

Direct seeding involves broadcasting dry seed or pre-germinated seeds and seedlings by hand or planting them by machine. In rain-fed and deep-water ecosystems, the dry seed is manually broadcast onto the soil surface and then incorporated either by plowing or by harrowing while the soil is still dry. In irrigated areas, the seed is normally pre-germinated prior to broadcasting.

2.6.3 Water and nutrient management

The rice plant needs water and nutrients for growth. Therefore, a water and nutrient management system, prevention of diseases and pests during rice cultivation are required. Cultivated rice is extremely sensitive to water shortages. To ensure sufficient water, most rice farmers aim to maintain flooded conditions in their fields. Good water management in the rice fields focuses on practices that conserve water while ensuring sufficient water for the crop. In rainfed environments when optimal amounts of water may not be available for rice production, a suite of options are available to help farmers cope with different degrees and forms of water scarcity. It includes sound land preparation and pre-planting activities followed by techniques such as saturated soil culture, alternate wetting, and drying, raised beds, mulching, and the use of aerobic rice that can cope with dryer conditions. For rice plant prevention, at each growth stage, the rice plant has specific nutrient needs. This makes nutrient management a critical aspect of rice farming. The unique properties of flooded soils make rice different from any other crop. Because of prolonged flooding in rice fields, farmers are able to conserve soil organic matter and also receive free input of nitrogen from biological sources, which means they need little or no nitrogen fertilizer to retain yields. However, farmers can tailor nutrient management to the specific conditions of their field to increase yields.

2.6.4 Harvesting

Harvesting is the process of collecting mature rice crops from the field. Depending on the variety, for riceberry rice a rice crop usually reaches maturity at around 130 days after crop establishment. Harvesting activities include cutting, stacking, handling, threshing, cleaning, and hauling. Good harvesting methods help maximize grain yield and minimize grain damage and deterioration. Harvesting can be done manually or mechanically.

Manual harvesting is common across Asia. It involves cutting the rice crop with simple hand tools like sickles and knives. Manual harvesting is very effective when a crop has lodged or fallen over, however it is labor-intensive. Manual harvesting requires 40 to 80 hours per rais, and it takes additional labor to manually collect and haul the harvested crop.

Mechanical harvesting using reapers or combine harvesters is the other option, but not so common due to the availability and cost of machinery. Following cutting the rice must be threshed to separate the grain from the stalk and cleaned. These processes also can be done by hand or machine.

Figure 3 Rice harvesting

2.6.5 Drying

Drying reduces the grain moisture content to a safe level for storage. It is the most critical operation after harvesting a rice crop. When rice is harvested, it will contain up to 25% moisture. High moisture levels during storage can lead to grain discoloration, encourage the development of molds, and increase the likelihood of attack from pests. It can also decrease the germination rate of the rice seed. Therefore, it is important to dry rice grain as soon as possible after harvesting within 24 hours. Delays in drying, incomplete drying or ineffective drying will reduce grain quality and result in losses. Paddy drying methods include traditional and mechanical systems with varying technological complexity and capacities for either farm or commercial level.

Figure 4 Rice drying

2.6.6 Storage

The purpose of the rice storage facility is to provide safe storage conditions for the rice in order to prevent grain loss caused by adverse weather, moisture, rodents, birds, insects, and micro-organisms like fungi. In general, it is recommended that rice for food purposes be stored in paddy form rather than milled rice as the husk provides some protection against insects and helps prevent quality deterioration (Rice Knowledge bank, n.d.)

Figure 5 Rice storage house

2.7 Organic riceberry production

Organic production is not simply the avoidance of conventional chemical inputs, nor is it the substitution of natural inputs for synthetic ones. It is based on minimal use of off-farm inputs and on management practices that restore, maintain, and enhance ecological harmony. Organic farmers apply techniques first used thousands of years ago, such as crop rotations and the use of composted animal manures and green manure crops, in ways that are economically sustainable in today's world. In organic production, overall system health is emphasized, and the interaction of management practices is the primary concern. Organic producers implement a wide range of strategies to develop and maintain biological diversity and replenish soil fertility (USDA, 2007). Organic production has the potential of developing a huge export and local market, creating employment opportunities in the rice industry. However, the productivity of this organic rice production is quite lower as compared with conventional rice production (Andersen *et al.*, 2015)

The general guidelines for organic rice production are indicated as follows:

2.7.1 Selection of rice species and farming areas

The rice species used for organic production should have the appropriate growth properties suitable for the environment in the farming area and produce good results even in relatively low fertility soil conditions. In addition, it must be resistant to diseases and insect pests to produce high-quality rice for consumers. Furthermore, the farming area is also important. Rice farming areas should have high nutrients of natural soil that are essential to the growth of rice adequately, there are water sources for planting, and should not be an area that has been used of chemicals for a long time or has high chemical contamination. In addition, the farming areas must be far away from areas where agricultural chemicals are used.

2.7.2 Soil preparation

The main objective of soil preparation is to make the soil conditions suitable for the planting and growth of rice. Helps in control of weeds, insects, diseases, and some rice enemies. Preparing more or less soil depends on the soil properties in the selected farming area, the environment in the rice field before planting, and the planting methods.

2.7.3 Farming methods

Transplanted is most suitable for organic rice production due to the preparation of the soil, the control of water level in the rice fields which help in reducing the number of weeds. This planting method also helps the rice to compete with weeds and pesticides. Seedlings that are used in the transplanted method should last about 30 days and be strong. In addition, organic rice production must avoid using all kinds of synthetic substances, especially chemical fertilizers. Therefore, in organic rice production planting must use longer period than conventional rice production. The distance between the tree and the row is about 20 cm. The number of seedlings is 3-5 trees per clump and uses a narrower spacing if the soil is relatively low fertility.

2.7.4 Soil fertility management

Because organic rice cultivation must avoid using chemical fertilizers, the selection of land plots with high natural abundance is advantageous for the beginning of rice farming. In addition, to maintain the level of productivity, farmers must know a good practice for soil management that are most effective and sustainable for growing organic rice. The recommendation on soil fertility management for organic rice production can be summarized as follows:

Soil management system usually adds more organic matter by planting other crops outside farming season such as legumes, green beans in the rice field. Then use the benefits from this organic matter for rice cultivation and to maintain the soil properties. In addition, avoid burning rice straw and rice stubble, and organic waste in the rice field. Because these activities will destroy organic matter and soil microorganisms.

Using natural organic fertilizers with a good management system. Examples of organic fertilizers are manure, compost and green manure from nature.

2.7.5 Cropping system

Growing organic rice only once a year by choosing the appropriate planting period for each rice species. In addition, to maintain the soil quality by planting other crops such as legumes, before and after rice cultivation to maintain soil fertilizer properties.

2.7.6 Prevention of disease, insect pests and weed control

Normally chemicals and insecticides were used for disease and insect pests' prevention. However, organic rice production must avoid using chemicals and insecticides. Therefore, important principles of disease prevention from insects and rice enemies in organic rice production used alternative methods such as select resistant disease rice species, good Agricultural management such as preparation of land, select the appropriate planting time and use the appropriate seed quantity and use technology for prevention of disease and insect pests. Moreover, weed control is also important for rice production. A suitable method for weed control is mechanical methods such as proper soil preparation, crop rotation, or using a water management system.

2.7.7 Water management

The water level is directly related to the growth of rice and the yield. In the transplanted rice period until the break of rice seed, if the water level is very high, it will make the rice plant high to escape the water, making the rice tree week and falling easily. At this stage, the water level should be maintained at about 5 cm. However, if the rice plant lacks water or lacks good water level management, the weeds will grow and destroy the rice plant. Therefore, the appropriate water level for organic rice cultivation during the growing season should be 5-15 cm during 7-10 days before harvesting.

2.7.8 Harvesting

Harvesting rice after 28-30 days after the grains are produced. Observed from the seeds in the rice grains if it turns into a straw colour. It's called the "Plab Prueng" phase. The harvesting methods consist of hand harvesting and mechanical harvesting. For hand harvesting, using the sickle for rice harvesting. It is having to dry the rice husk in the field for about 2-3 sunny days and then continue to rice threshing. For mechanical harvesting, using a tractor car for rice harvesting will cause the rice seeds to have high moisture content. Therefore, it must be dried in high sunny conditions for 1-2 days. Turn the rice seeds 3-4 times a day, to reduce the moisture to 14 percent or lower to be suitable for storage and make good colour quality.

2.7.9 Storage

Lowering the moisture content of rice to below 14 percent, then put the grain to be stored in the rice storage house. This important step must avoid the storage of rice from the rice produced by other methods.

2.7.10 Rice processing and packaging

In the rice processing or milling process, organic rice must separate from other rice in conventional rice production. Before starting the milling process of organic rice, producers must use paddy organic rice milling for cleansing the rice mill machine before the rice milling process. After the rice was milled, rice should be pack in small bags from 1 kg to 5 kg and packed in a vacuum condition to avoid contamination from pollution (Organic Rice Research Institute, 2018)

2.8 Riceberry products

Riceberry processing contributes to creating more value-added to riceberry rice. In addition, innovation and technology for processing of riceberry rice has expanded the rice market for more export volume.

The group of riceberry processed products can be divided into 6 groups as follows:

1) Rice based food such as porridge ready to eat, ready-to-eat rice in canned

2) Rice flour food such as rice noodle, spaghetti, packaged food and others

3) Oil such as rice bran oil and others

4) Rice snacks such as cookies, snack bar, bread and others

5) Beverages from rice such as rice milk, rice milk powder, tea and alcoholic beverages

6) Other's products such as health supplement food, shampoo, soap and cosmetics (Sangkaman, 2016)

The definition of innovation processed products from riceberry rice can be divided into 2 types as follows:

Value-added products or products that use technology for increase the value-added including the use of food science technology to extend the shelf life of the products in various ways, such as pasteurization, sterilize, vacuum packaging design of packaging etc.

Value creation product or riceberry products that use innovation and technology to change riceberry rice or waste into a new variety of products. These new products may not be in the form of rice it can be processed into both food and non-food products such as snacks, riceberry juice, noodles or even cosmetics and soaps etc (Rawangsamrong, 2018). The flow chart of riceberry products are shown in **Figure 6**.

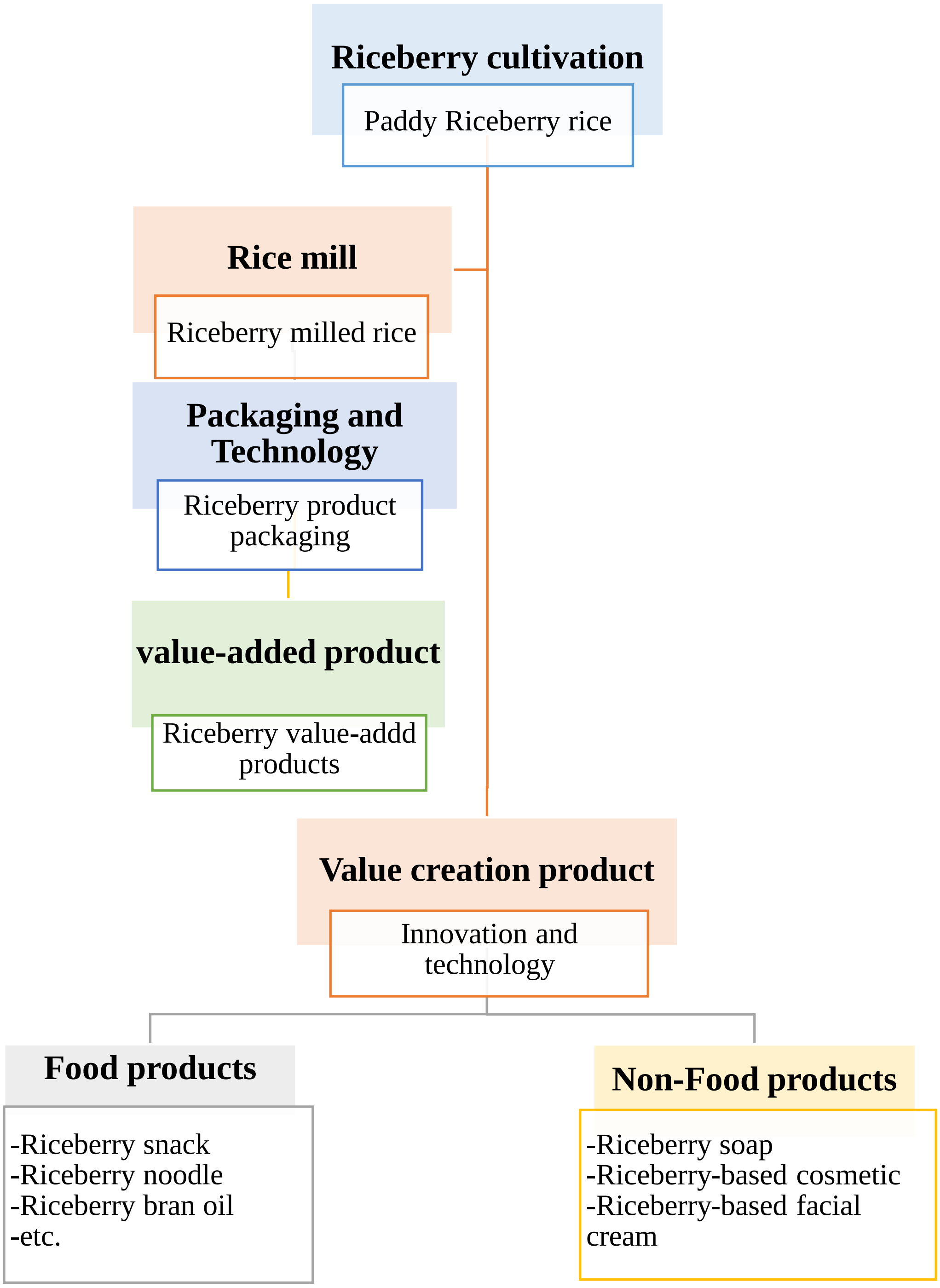

Figure 6 Riceberry products flowchart

The example of riceberry products in value creation products consist of food and non-food as shown in **Figure 7.**

Food-Product		
 Riceberry juice	 Riceberry rice bran and germ oil	 Riceberry Granola
 Sun bites plus (Riceberry)	 Riceberry wheat loaf	 Riceberry porridge
Non-Food Product		
 Mistine Riceberry milk	 Riceberry cream scrub	 Snowgirl Riceberry facial cream
 Riceberry soap with honey	 Coco-Riceberry shampoo	 Riceberry crackers

Figure 7 Riceberry products

2.9 Potential markets for riceberry products

There are several riceberry products both food and non-food products available in the market. However, many types of riceberry products in the market are still concentrated in the intermediate products such as snack, beverage, noodle, flour, and dessert, etc. as shown in **Figure 7**. Moreover, at present, the trend of consumers in the market has shifted in their preferences towards a healthy and nutrition-rich diet. In order to meet that demand of consumers, especially for a niche consumer (niche market), and provide the general consumers with more choices of agricultural products. Thailand needs to focus on the development of innovation and technology and provide more knowledge to rice farmers and producers. Therefore, riceberry product producers need to consider the customer preference and the trend of buyers that are changing in the market transformation. Changing of consumer behavior and marketing channel in the rice market can be summarized as follows:

1) More alertness and health consciousness trend in food selection

Nutrition and bad dietary habits have the greatest influence on weight gain and obesity, which are serious public health problems (Lorinczi, 2008). The consumer way of life and health are relevant factors affected the food choice selection and health-conscious trend on food consumption. Therefore, health-conscious consumers in rice market will focus on quality and safe rice products before buying such as organic riceberry products and prefer more functional food.

2) Urban society hustle

The hustle and bustle of the people's lifestyle in the city causes little time to prepare food. Including the expansion of the middle class in the society, most consumers turn to consuming more instant foods, ready-to-cook meals and ready-to-eat meals.

Furthermore, as a part of the consumers' preference, the marketing channel is also the key factor affected riceberry rice market. Marketing channel is a system which ensures the distribution of the merchandise from the producers to the consumers by passing it through multiple levels known as middlemen (Prachi, 2018) It is also known as channels of distribution consist of domestic and export market. As shown in **Figure 8** the value chain flow chart of riceberry rice start from rice farmers, local trader, rice mill and processing factory but the most importance stage connecting between producers and consumers is the market. In this study, the marketing channel can be divided into 4 categories as follows:

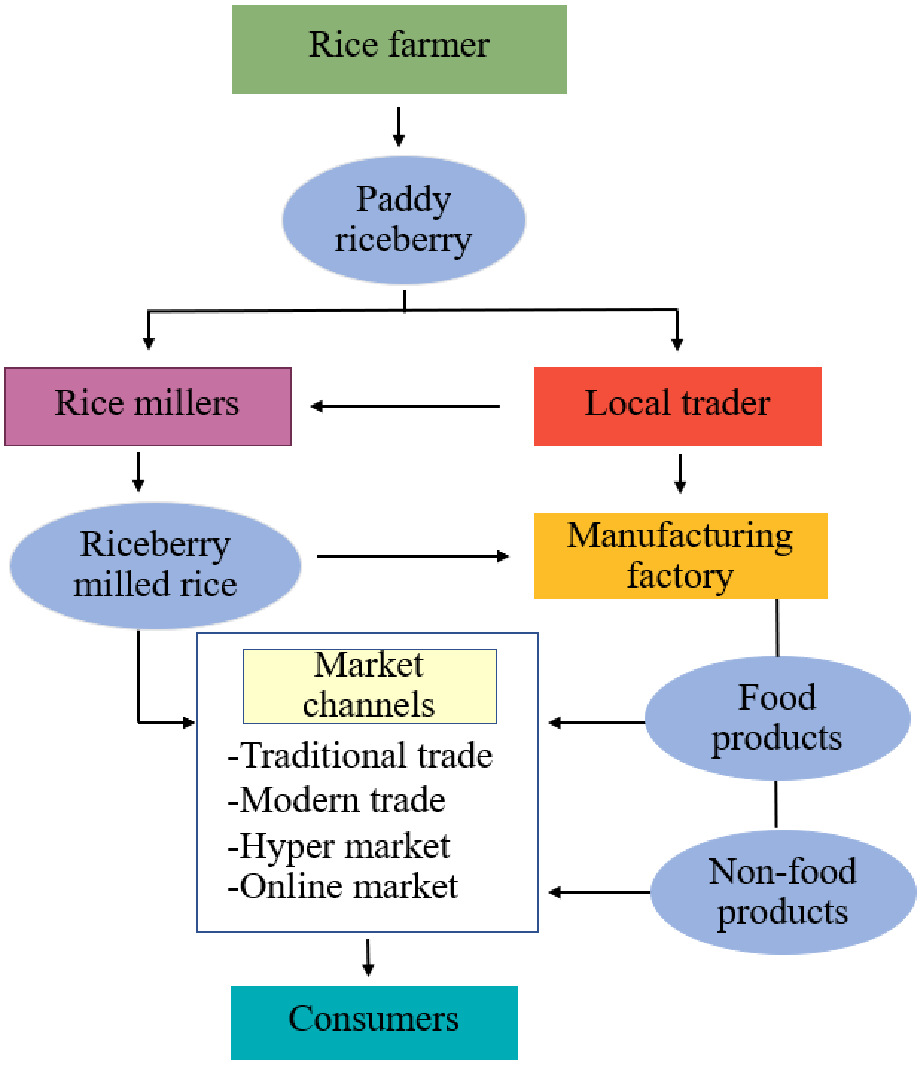

Figure 8 Value chain flowchart of riceberry rice

1) Traditional trade

Traditional trade is a complex distribution network of micro-retailers, kiosks, hawkers, stockists, open market traders, wholesalers, and distributors. Traditional trade builds on interpersonal relations between the customers and the retailers. Traditional trade is less organized than modern trade and is more likely to run out of stock or push alternative products to customers.

2) Modern trade

Modern trade outlets are chains or groups of businesses. They include larger players such as hypermarkets, supermarket chains, and mini markets. Retail operations are more planned and operations use a more organized approach to inventory management, merchandising, and logistics management (Nieuwoudt, n.d.)

3) Hyper market

A hypermarket is a retail store that combines a department store and a grocery supermarket. Often a very large establishment, hypermarkets offer a wide variety of products such as appliances, clothing, and groceries. Hypermarkets offer shoppers a one-stop shopping experience (Kenton, 2020)

4) Online market

At present, many consumers' behavior has changed to online shopping due to the convenience of the online ordering system. Therefore, riceberry products producers should prepare suitable products for this marketing channel. For example, many existing advanced processed products that suitable for this marketing channel are ready to eat food, cosmetics, medicine, and other products that ease-to-distribute between producers and consumers (Kasikorn Research Institute, 2020)

2.10 National policy on sustainable rice production

In the past, several Thai agricultural policies from each government aimed at the restructuring of the rice production system by providing some incentives support and direct subsidy to rice farmers. For example, the paddy pledging policy allow Thai farmers the opportunity to pledge and then provide an unlimited supply of their rice to the government at a higher price for their crops than they would obtain by selling them at market rates. The goal of the scheme was to increase rice prices to safeguard farmers from middlemen (Poapongsakorn, 2019). However, the directed support policy to the producers, rice farmers from the government is not sustainable for the rice industry in long-term development. Sustainable development should be considered in long term. At present, Thai agricultural policy has shifted from producers supported to sustainable policy aimed at the restructuring of the Thai rice industry to a value-based economy. The related policy consists of the Thai rice strategic policy which focuses on the development of value-added products from rice with the aims to increase both quantities, quality, and value-added of rice and Thailand 4.0 policy which focuses on economic restructuring from the industrial economic driven into creativity, innovation and technology driven. The main content of these policies is explained as follows:

2.10.1 Thai rice strategy policy

The goal is to make Thailand a world leader in the production and marketing of quality rice and rice products, in four areas: foreign marketing, domestic marketing, production and processed products, and innovations from rice. The key strategy related to rice production and products can be summarized as follows:

Strategy 1: Research and development

The purpose of this strategy is for farmers and entrepreneurs to have knowledge and innovation in rice development that is consistent with Thailand's production system. In addition, farmers and entrepreneurs can apply the knowledge to effectively answer the preferences of consumers in both domestic and export markets. The expected outcome from this strategy is new rice varieties with high quality and production yield and new processing technology with at least 8 new rice processed products. In addition, the strategy aimed at accelerating the research and improving the efficiency of rice production. Including, increase the value-added to Rice products and, the development of farmers.

Strategy 2: Development of rice production and rice products

The purpose of this strategy is farmers and entrepreneurs can produce rice and rice products, increasing both quantity, quality, and value with lower production cost. The expected outcome from this strategy is to increase rice production yield by at least 10% and reduce the production cost of rice farming. In addition, increase the efficiency of the management of rice and rice products for farmers and promote the use of technology in rice production and products supporting the development of rice production machinery including improving the efficiency of technology transfer and knowledge management to farmers. To publicize the value of rice products.

Strategy 3: Strengthen of rice farmers

The purpose of this strategy is to strengthen rice farmers and entrepreneurs in rice production and provide the ability to effectively management of their productivity. The expected outcome from this strategy is rice farmers receive academic knowledge support for self-development (Department of Rice, 2012).

2.10.2 Thailand 4.0 policy

Thailand 4.0 is the government's ambitious 20-year strategy, this Thailand 4.0 policy was promoted to become a formal and certified national policy to accelerate Thailand's development to a more advanced level (Royal Thai Embassy, n.d.). Moreover, Thailand 4.0 policy is a sector-specific vision to transform the Thai economy, pulling it out of the middle-income trap and developing it into an innovative, dynamic, high-income country. The main objectives of Thailand 4.0 are creating a value-based economy by changing from driving the country with the industrial sector into the country that is driven by innovation, technology, and creativity. The key parts of the Thailand 4.0 model emphasize "security, wealth and sustainability" with the aim to create a value-based economy by economic restructuring from the industrial economy driven into creativity, innovation, and technology (Rawangsamrong, 2018).

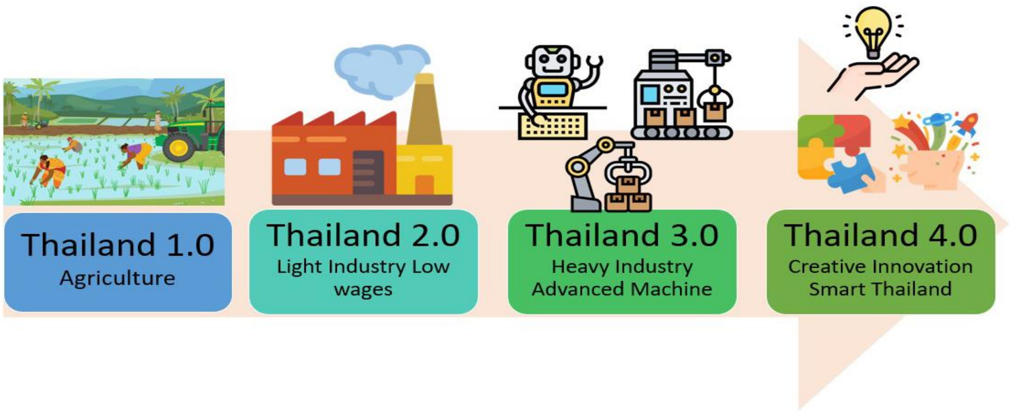

Figure 9 Thailand 4.0 model

The goals of Thailand 4.0 are to focus on transforming the social welfare system by turning traditional farmers into smart farmers, traditional SMEs to startups, and going from low-value services to high-value services to achieve "sustainable growth and development" without damaging the environment. In addition, to transition from commodities products to innovative products. Therefore, the development of Thai rice production and exports according to the Thailand 4.0 policy should be focused on the development of cultivation practices, harvesting, storage, and processing, as well as export processes by using more technology or innovation and creative thinking in each step. For example, in the past, rice farmers only grew rice to sell as paddy rice or milled rice. They must change to create high value-added products with technology, innovation, and creativity. In addition, rice farmers also need the improvement of knowledge, technology, and understanding of good agricultural practices of quality and safe rice for consumers or simply called "Smart

Farmer" (Thanaboonyawat, 2019). From this concept, Thailand 4.0 policy applied to the riceberry rice industry must be a transition in 4 key elements.

1) Change from traditional farming to new innovative agricultural farming or smart farming. In addition, farmers must have more income from high value-added products.

2) Change from traditional SMEs with government support all the time to smart enterprise or start-up businesses with high potential for innovation-driven.

3) Change from Traditional services with low value-added to high value-added services
4) Change from low-skilled workers to highly skilled workers with the knowledge, expertise, and highly skills

3. Sustainability assessment tools

3.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is an environmental analysis tool to assess the potential environmental impacts of a product or service associated with the inputs and outputs of a product system. The methodology framework of LCA is standardized and described in ISO 14040/14044: 2006. The scope of analysis covers throughout the life cycle of product or service from raw material acquisition, production process, distribution, use and consumption, and final disposal stage including related transport in all stages (cradle-to-grave). It is particularly important to (a) identify opportunities to improve the environmental performance at different stages of the product’s life cycle, (b) inform decision-makers in industry or institutions (e.g., to design or redesign the product or process), (c) help to choose significant indicators of environmental performance, and (d) assist in marketing. The principal application of LCA is to compare environmental profiles of alternative products or services that have equivalent functions. The framework of the methodology, according to ISO 14040/ 14044:2006, can be divided into four main steps (**Figure 9**) as follows:

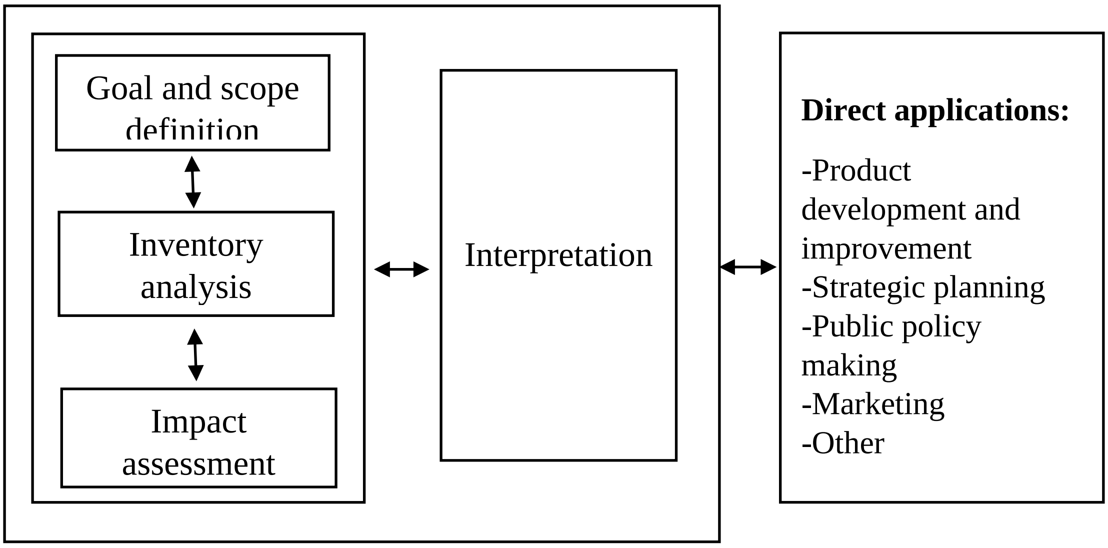

Figure 10 Phases of an LCA

3.1.1 Goal and scope of the study

The goal and scope should be defined, including the function unit and system boundary. The purpose of the LCA study will identify the necessary inventory data and impact assessment. The first step of the goal and scope definition stage is to state and justify the goal of the LCA study. This step explains the study's objective and indicates the intended use of the results or application. The scope definition considers and describes the functional unit, system boundaries, data quality requirements, and comparison between product systems.

3.1.2 System boundary of LCA

The system boundary of an LCA study defines the step by steps of the unit process and should be consistent with the goal and scope of the study. The way that the system boundary is established must be identified and explained. The definition of system boundary is made through a meticulous characterization of the product system, including the identification of manufacturing processes and flow diagrams. The types of system boundaries are shown as follows:

Cradle-to-grave

Full LCA from raw material extraction through materials processing (raw material acquisition, production process, distribution, use and consumption, and final disposal stage including related transport in all stages).

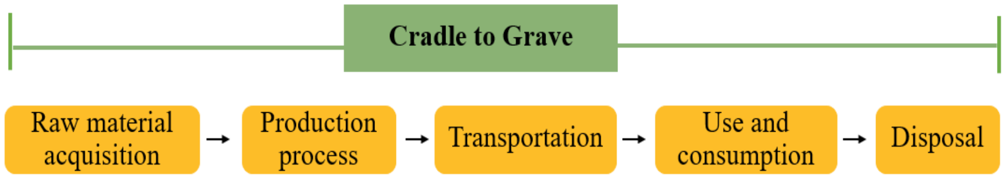

Figure 11 The LCA system boundary based on cradle-to-grave

Cradle-to-gate

Partial LCA from resource extraction (cradle) to the factory gate (Raw materials acquisition, and production process in products system)

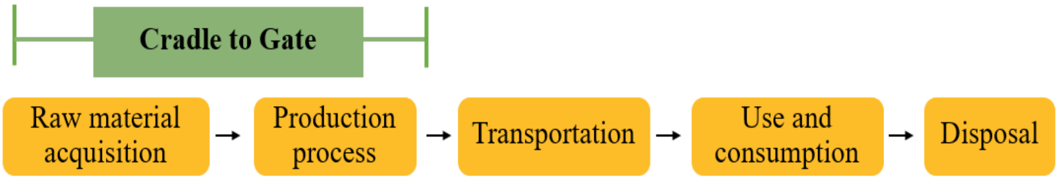

Figure 12 The LCA system boundary based on cradle-to-gate

Gate-to-gate

Partial LCA consider only one process in whole production chain such as production process of on products system.

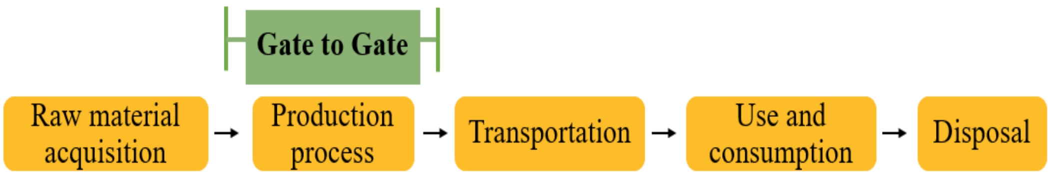

Figure 13 The LCA system boundary based on gate-to-gate

3.1.3 The Functional unit

A functional unit is a measure of the performance of the functional outputs of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed to ensure that such comparisons are made on a common basis.

3.1.4 Life Cycle Inventory (LCI) analysis

This stage aims to collect input/output data according to the defined system boundary, such as raw material use, energy use and waste. The inventory analysis, also known as Life Cycle Inventory (LCI), is the most important phase of the LCA study. The LCI identifies the inputs and outputs to be considered in the product system under study. The LCI phase compiles all the important data in order to perform the LCA study and therefore a list containing the quantities of energy and materials consumed as well as pollutants released to the environment. The relevant steps of the LCI phase include flow diagrams, data collection, cut-off, data estimation and allocation. The process of data collection can begin once the model structure is described. A balance sheet of inputs/outputs is created for each unit process of the study. According to ISO 14044 (2006), the qualitative and quantitative data used in the inventory should be collected for each unit process included in the system boundary.

The process of data collection can begin once the model structure is described. A balance sheet of inputs/outputs is created for each unit process of the study. According to ISO 14044 (2006), the qualitative and quantitative data used in the inventory should be collected for each unit process included in the system boundary. This data is used to quantify the inputs and outputs of a unit process, whether it is measured, estimated or calculated. At present, the data is always collected through questionnaires answered by various technicians, responsible for the manufacturing process. LCI are sourced from primary and secondary data. Primary data are collected from direct measurement in the system boundary. Secondary data is the data which come from other sources such as literature.

3.1.5 Allocation

Allocation is essential when dealing with a system involving multiple products or multifunctionality. The materials and energy flow as well as associated environmental releases shall be allocated to the different products according to clearly stated procedures, which shall be documented and justified. According to ISO 14044:2006, multifunctionality should be solved by using the following three-level hierarchy

1) Avoiding allocation by subdivision (dividing the unit process into two or more sub-processes) or system expansion (expanding the product system to include the additional functions related to the co-products)

2) Allocation following underlying physical relationships (i.e., an allocation that quantitatively reflects how the inputs and outputs are changed by changes in the amount of each product of the system)

3) Allocation (partitioning) based on other relationships (e.g., economic value)

Table 7 Mass allocation procedure

Product	**Quantity**	**% of allocation**
X	A	A/(A+B) ×100
Y	B	B/(A+B) ×100

Table 8 Economic allocation procedure

Product	**Quantity**	**Price**	**% of allocation**
X	a	A	aA/(aA+bB) ×100
Y	b	B	bB/(aA+bB) ×100

3.1.6 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is the stage of evaluation of potential environmental impacts and human health from the identified LCI analysis by converting the LCI results into specific impact indicators. Conducting LCIA has to follow several sub-steps: The first is to select impact categories for analysis. The basic impact categories indicators are shown in **Table 9**. The second is to assign the LCI results to different impact categories (classification). The third, the potential impact indicators are calculated (characterization). These three steps are mandatory for LCIA. Also, there are optional steps for LCIA, including relating the impact indicators to reference conditions (normalization), grouping, and weighting impacts, as shown in **Figure 14.**

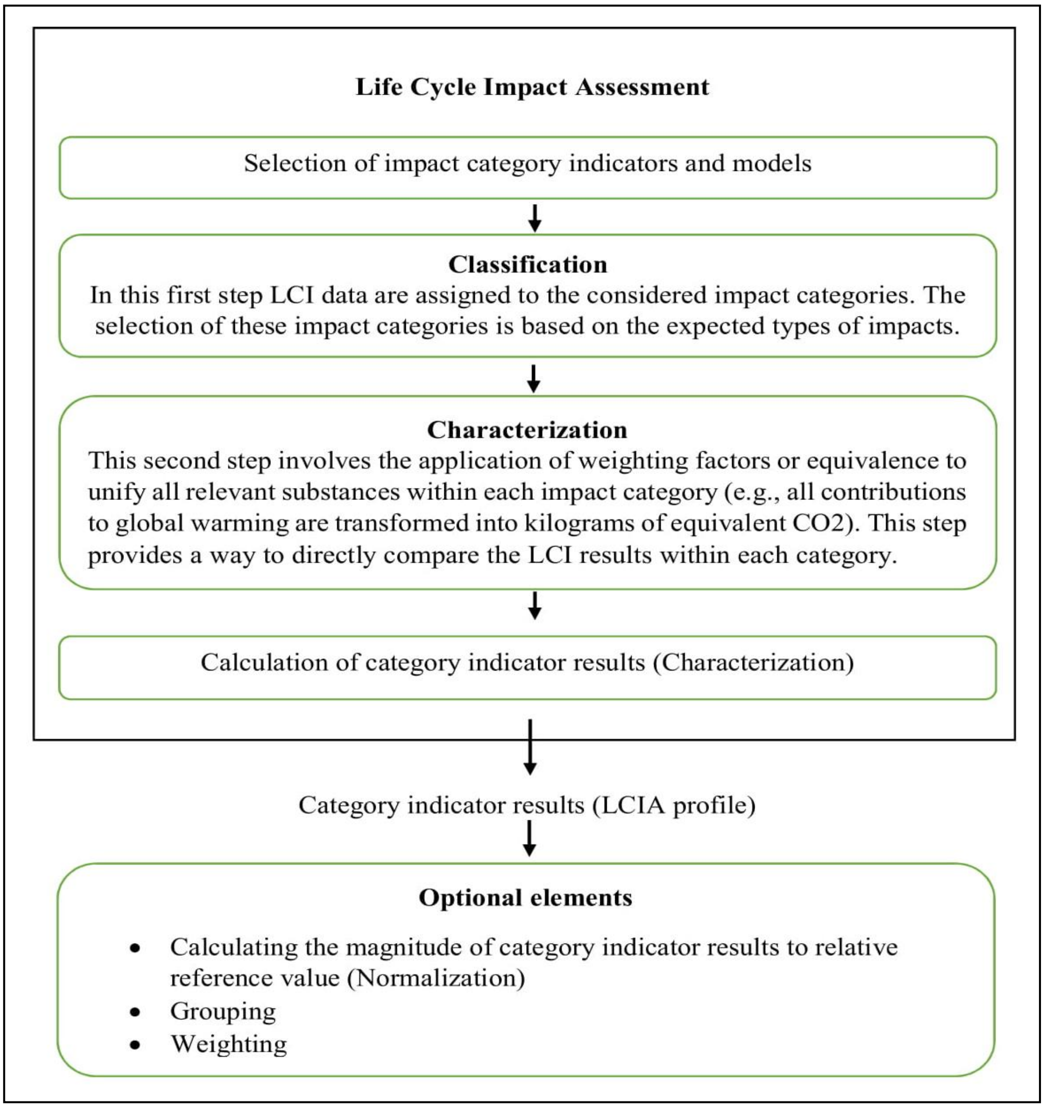

Figure 14 LCIA methods

Table 9 Basic life cycle impact assessment indicators

Environment Impact Category	Explanation
Abiotic Depletion Potential	The acquisition of non-renewable raw materials.
Energy Depletion Potential	Acquisition of energy resources
Global Warming Potential	Infrared absorption in atmospheres that cause global warming.
Ozone Depletion Potential	Reduction of ozone in the stratosphere that makes infrared rays shine through our world.
Human Toxicity	Exposure to air, water and soil pollutants causing adverse effects on human health.
Aquatic/Terrestrial Eco-toxicity	Exposure to air, water, and soil pollutants causing effects on plants and animals on land and in water.
Acidification Potential	Acid rain
Photo-chemical Oxidation	Ozone depletion in the troposphere cause the smog photochemical phenomenon
Eutrophication	The increase in mineral nutrients in the water causes the rapid growth of phytoplankton leading to the reduction of oxygen in the water.

Environmental Impact Assessment Methods

The LCIA methods were developed by various organizations and already available for use as impact assessment methods. The examples of the LCIA methods are shown in **Table 10**

Table 10 The examples of read-made LCIA methods

Method	**Background publication**
CML 2001	Guine´e *et al.,* 2001
Cumulative Energy Demand (CED)	Frischknecht R *et al.,* 2003
Eco-indicator 99	Geodkoop & spriensma, 2007a; b
EF Method	EC, 2016
IPCC 2013 GWP100a (Global Warming Potential)	(IPCC, 2013)
ReCiPe 2016	Pre consultant, CML RIVM & Radboud University, 2016

Products Environmental Footprint (PEF)

Products Environmental Footprint (PEF) is selected to the life cycle impact assessment method to be used in this study. There are two mandatory steps for this method: classification and characterization, and two optional steps: normalization and weighting (The European Commission, 2016). In the classification step, the material or energy inputs and outputs inventoried in the LCI are assigned to one or more relevant impact categories. An important part of the classification step is expressing the data in terms of constituent substances for which the characterization factors are available. All classified inputs/outputs were calculated using the characterization factors for the magnitude of the contribution of each EF impact category (Pyay *et al.,* 2019). The EF impact assessment models are shown in **Table 11**.

Table 11 EF impact assessment models for PEF studies

EF Impact category	EF Impact assessment model	EF Impact Category indicators	Source
Climate Change	Bern model – Global Warming Potentials (GWP) over a 100-year time horizon.	kgCO_2 equivalent	Intergovernmental Panel on Climate Change, 2007
Ozone Depletion	EDIP model based on the ODPs of the World Meteorological Organization (WMO) over an infinite time horizon.	kgCFC-11 equivalent	WMO, 1999
Ecotoxicity for aquatic fresh water	USEtox model	CTUe (Comparative Toxic Unit for ecosystems)	Rosenbaum *et al.*, 2008
Human Toxicity - cancer effects	USEtox model	CTUh (Comparative Toxic Unit for humans)	Rosenbaum *et al.*, 2008
Human Toxicity – non-cancer effects	USEtox model	CTUh (Comparative Toxic Unit for humans)	Rosenbaum *et al.*, 2008
Particulate Matter/Respiratory Inorganics	RiskPoll model	kg PM2.5 equivalent	Humbert, 2009
Ionising Radiation – human health effects	Human Health effect model	kg U235 equivalent (to air)	Dreicer *et al.*, 1995
Photochemical Ozone Formation	LOTOS-EUROS model	kg NMVOC equivalent	Van Zelm *et al.*, 2008 as applied in ReCiPe
Acidification	Accumulated Exceedance model	mol H^+ eq	Seppälä *et al.*,2006; Posch *et al.*, 2008
Eutrophication – Terrestrial	Accumulated Exceedance model	mol N eq	Seppälä *et al.*,2006; Posch *et al.*, 2008
Eutrophication –	EUTREND model	fresh water: kg P	Struijs *et al.*, 2009

Aquatic		equivalent marine: kg N equivalent	as implemented in ReCiPe
Resource Depletion – Water	Swiss Eco scarcity model	m^3 water use related to local scarcity of water	Frischknecht *et al.*,2008
Resource Depletion – mineral, fossil	CML2002 model	kg antimony (Sb) equivalent	van Oers *et al.*,2002
Land Transformation	Soil Organic Matter (SOM) model	kg (deficit)	Milà i *Canals et al.*,2007

Source: The European Commission, 2016

3.1.7 Interpretation

Life Cycle Interpretation is a systematic technique to identify, quantify, check, and evaluate information from the results of the life cycle inventory and/or the life cycle impact assessment. The results from the inventory analysis and impact assessment are summarized during the interpretation phase. The outcome of the interpretation phase is a set of conclusions and recommendations for the study. Moreover, the interpretation should deliver results that are consistent with the defined goal and scope and reach the conclusions. There are two objectives of the interpretation phase: first, to analyze results, reach conclusions, explain limitations, provide recommendations and second, to provide a readily understandable, complete and consistent presentation of the result of an LCA study in accordance with the goal and scope of the study (Paoluglam, 2005)

3.2 Eco-efficiency assessment

Eco-efficiency is a sustainability measure combining environmental and economic performances. It promoted a transformation from unsustainable development to one of sustainable development based on the concept of creating more goods and services while using fewer resources and creating less waste and pollution. Eco-efficiency can be seen either as an indicator of the environmental performance or as a business strategy for sustainable development (Koskela, 2012).

The framework of methodology, according to ISO14045:2012, can be divided into five main steps (**Figure 15**) as follows:

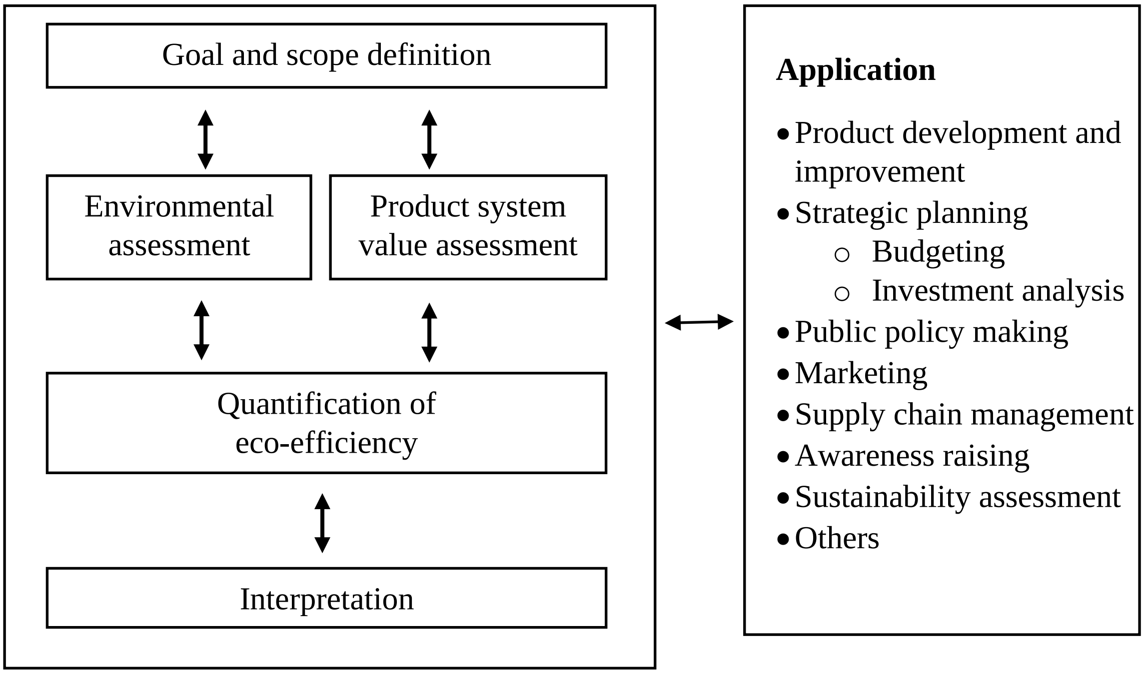

Figure 15 Eco-efficiency Assessment

3.2.1 Goal and scope definition

The goal and scope definition of eco-efficiency assessment, including the functional unit and system boundary of the study. The purpose of eco-efficiency assessment should be defined by this step. Including, The intended use of the result from eco-efficiency assessment.

3.2.2 Environmental assessment

This step of eco-efficiency assessment is to evaluate the environmental impacts of products. The environmental assessment method is based on the LCA methodology described in ISO14040 and ISO14044.

3.2.3 The product system value assessment

The product system value assessment shall base on the full cycle of the product system. The objective of products system value assessment is to convert the value of products to quantitative figures based on the function of products. The product's system value should be consistent with the goal and scope defined. The product system value assessment can be divided into three types, as follows:

It can be the economic value of products or systems based on the purpose of eco-efficiency being used.

The example of product system value types are as follows:

1) The functional value

The functional value is defined as the value of the product by considering the indicators that reflect the functionality, product development, or improvement in quantitative figures, for example, product performance measurement, product lifetime, and others.

2) Monetary value

The monetary value is defined as the value of the product by considering the indicators that reflect financial or monetary value in accounting or economic figures, for example, production cost, selling price, product value-added, profits, and others.

3) Other's value

Other's value is defined as the value of product by considering the quantitative indicators that reflect the product's intangible value, for example, the beauty of products, branding, and cultural value.

3.2.4 Qualification of eco-efficiency

The eco-efficiency results shall be determined by using the results of the environmental assessment and the results of the product system value assessment according to the goal and scope definition. The eco-efficiency calculation can be calculated as shown in Equation (1)

Eco-efficiency = Selling price/Environmental impacts indicator (1)

3.2.5 Interpretation

The interpretation phase of an eco-efficiency assessment is an identification of significant issues based on the results of the environment and product system value. The outcome of the interpretation phase is the formulation of the conclusion, limitations, and recommendations of the eco-efficiency assessment results.

4. Previous studies on LCA & Eco-efficiency in rice production and agricultural products

LCA has been applied to the agricultural sector to identify the source of the environmental impacts. The global warming potential, one of the main source is CH_4 emission from flooded rice fields, There are many LCA studied was mainly focus on GHG emission from rice and grain production system especially in the rice field, LCA study of 1 kg paddy rice (Khao Dawk Mali 105) with the scope from cradle-to-farm gate showed that the total GHG emissions was 0.58 kg CO_2e per kg of paddy rice, with the major source from the rice field accounting for 83% of the total, followed by land preparation, harvesting and other stages (planting, cultivation, and transport of raw materials) were 9, 5 and 3% of the total, respectively (Yodkhum *et al.*, 2017). The study results are similar to the carbon footprint of grain production in China, the GHG emission equal to 0.48 kgCO_2e/kg for maize, 0.75 kgCO_2e/kg for wheat and 1.60 kgCO_2e/kg for rice (Zhang *et al.*, 2017). However, comparing to the LCA result of 1 kg Organic Hom Mali rice in Thailand, it was indicated that the magnitude of GHG emissions equals 2.88 kgCO_2eq/kg. The higher GHG emission in rice field was resulted from the use of green manures from rice straw and cattle manure used to improve the nutrient level in soil (Mungkung *et al.*, 2019). Similarly, LCA of paddy rice production in the northeast of Thailand also found that 1 kg of paddy rice in rainfed season was equal to 2.97 kgCO_2eq/kg while the paddy rice production in wet and dry season irrigated rice was equal to 4.87 and 5.55 kgCO_2eq/kg (Thanawong *et al.*, 2014).

Apart from GHG emission in rice fields, the production of rice both in the rice milling stage and rice processing also causing significant environmental impacts. LCA was also applied to the processing products from rice and grains, Kamalakkannan & Kulatunga, (2018) studied LCA of 1 kg milled rice by setting the system boundary to cover from gate to gate and reported that the parboiling process was the most significant effect on the environment by generating the highest GHG emission ranging from 0.0269-0.0713 kgCO_2e, follow by 0.0711-0.0206 kgCO_2e in rice polishing process. Jeswani *et al.*, 2015 studied the LCA of breakfast cereals, the results indicated that the average global warming potential equal to 2.64 kg CO_2e. per kg of product with the main hotspots causing from rice production (48%) used as main ingredients, energy consumption in the manufacturing process for 23%, while packaging and transportation contribute to 15% of each. In a similar study, the LCA result of 125 g dry ready-made porridge showed that the global warming potential of dry porridge equal to 0.141 kgCO_2eq/pack. The main hotspot of environmental impact caused by the raw materials was higher than for the wet alternative because of the energy consumption in milk powder production. Moreover, the cultivation of other agricultural products also identified as another hotspot causing significant impacts on the environment (Sieti *et al.*, 2019).

For non-food products, the carbon footprint value of the macadamia soap bar equal to 0.741 $kgCO_2e$, while the water footprint result was 1.581 L, 1.587 L, and 3.672 L for the green, blue, and gray components, respectively. The main hotspot of carbon and water footprint in this study was significantly high in the farming stage, mainly due to the fertilizers used for palm cultivation and the high energy demand of the fertilizer production. Moreover, water demand was the main requirement for the agricultural farming (Francke, *et al.*, 2013).

In Thailand, eco-efficiency has been applying for identifying the most sustainable management system in agricultural products. For example, the result of eco-efficiency assessment on paddy rice production under the irrigation and rain-fed conditions reported that the eco-efficiency of the wet-season rain-fed system equal to 4.04 baht/$kgCO_2eq$. While wet-season irrigated systems and dry-season irrigated systems equal 2.46 and 2.16 baht/$kgCO_2e$ respectively. The more eco-efficient of wet-season rain-fed system than others due to lower GHG emission generated in the rice fields (Thanawong *et al.*, 2014). For other agricultural products, the main hotspot causing GHG emission is fertilizer use from integrated orchards system which resulted in a lower eco-efficiency value equal to 7.2 (±2.7) NZD net profit per $kgCO_2$ e for integrated orchards. While organic orchards were significantly higher with the eco-efficiency value equal to 25.5 (±8.9) NZD net profit per $kgCO_2e$. (Müller *et al.*, 2015). Similarly, Ho *et al.*, (2018) analyzed the difference in eco-efficiency between conventional and sustainability-certified coffee production in Vietnam. The result showed that sustainability-certified coffee farms are more eco-efficient than conventional farms due to a 50 reduction of environmental impacts each year while maintaining the constant value-added of products.

MATERIALS AND METHODS

MATERIALS

Materials use for Thesis implementation are divided in 2 categories consist of:

1. Materials for data collection

   1.1 Life cycle inventory data collection table

2. Materials use for Life cycle assessment and Eco-efficiency assessment

   2.1 Computer

   2.2 SimaPro software version (9.0.0.35)

   2.3 Literature review document and standard document for calculation

METHODS

This study was accomplished through two main steps. Firstly, a Life Cycle Assessment (LCA) from cradle-to-grave was performed according to the ISO 14040–14044 (ISO, 2006a, b) and product environmental footprint, PEF version 2.0 (The European Commission, 2016) was used as the impact assessment method for assessing the environmental performances of each riceberry products. Secondly, the eco-efficiency assessment analysis was performed according to the method described step-by-step in ISO 14045 (2012) (ISO, 2012) and combined with LCA for evaluating the environmental and economic performances of riceberry products. The details of the two methods are provided in the sections below.

1. Life Cycle Assessment (LCA)

1.1 Goal and scope definition

The aim of this study was (1) to assess the environmental performance of 4 riceberry rice processed products throughout the life cycle as shown in **Figure 16.** (2) to compare environmental performance of original products and after improvement products (3) to evaluate the integration of environmental and economic performances, expressed as the eco-efficiency values of riceberry processed products to provide the decision supporting information to improve environmental and economic performances for private companies and to suggest which products should be further developed and promoted to move towards sustainability for policymakers.

(a) Riceberry soap

(b) Riceberry hair conditioner


(c) Riceberry snack bar

(d) Riceberry porridge

Figure 16 Food and non- food riceberry products for this study: which were riceberry soap (a), riceberry conditioner (b), riceberry snack bar (c), and riceberry porridge (d)

1.2 System boundary

The system boundary was the whole life cycle of riceberry processed products production or the "cradle to grave" as shown in **Figure 17**, covering the raw material acquisition, production process, distribution, use or consumption, and final disposal, including the related transports in all stages. The details of each step are explained as follows. Firstly, the raw materials used for each product (i.e., agricultural ingredients) were sourced from local suppliers, then all materials were transported to the production site. The production process of each product is described in **Figures 18-21**. All riceberry products were distributed to the distribution center or retail store where the consumer can purchase and order via online shipping. In the use and consumption stage, food products consumption is following the product's instructions, for example, riceberry porridge was using 100 ml of boiled water for 3 minutes before consumption. The use phase of other products was assumed by following the method specified in the Product Category Rules Household Cleaning Products (PCR) (TGO, 2017). For the final waste disposal, it was assumed packaging waste after use and consumption was transported to the landfill.

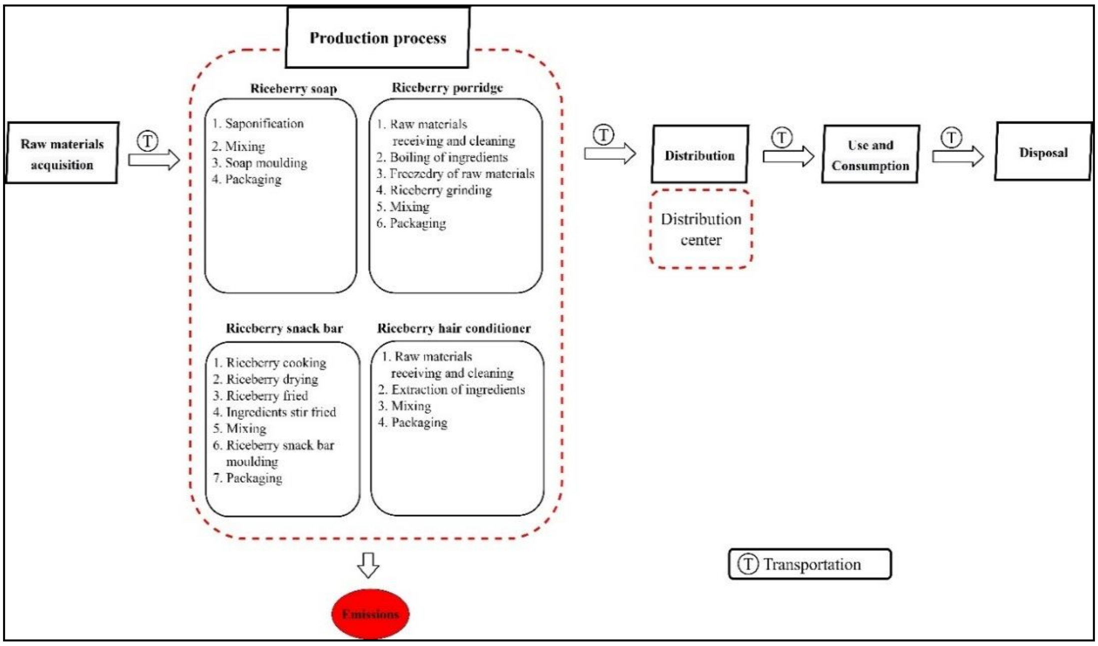

Figure 17 System boundary and main stage for the LCA study of Riceberry products

1.2.1 Riceberry soap

The production of riceberry soap, by using a cold processing method, consisted of four stages including saponification, mixing, molding, and packaging as shown in **Figure 18.** In the first stage, Sodium hydroxide (NaOH) 100% was mixed with water in a mixer pot at room temperature which caused a chemical reaction called saponification. Then, it was mixed with other soap ingredients in the mixing stage consisting of oils and others; at this stage, the output product was a liquid riceberry soap. Later on, liquid riceberry soap was dried in a soup molding for 1 day and the finished product is 90 g of riceberry soap. Finally, riceberry soap was packed in kraft paper for sale.

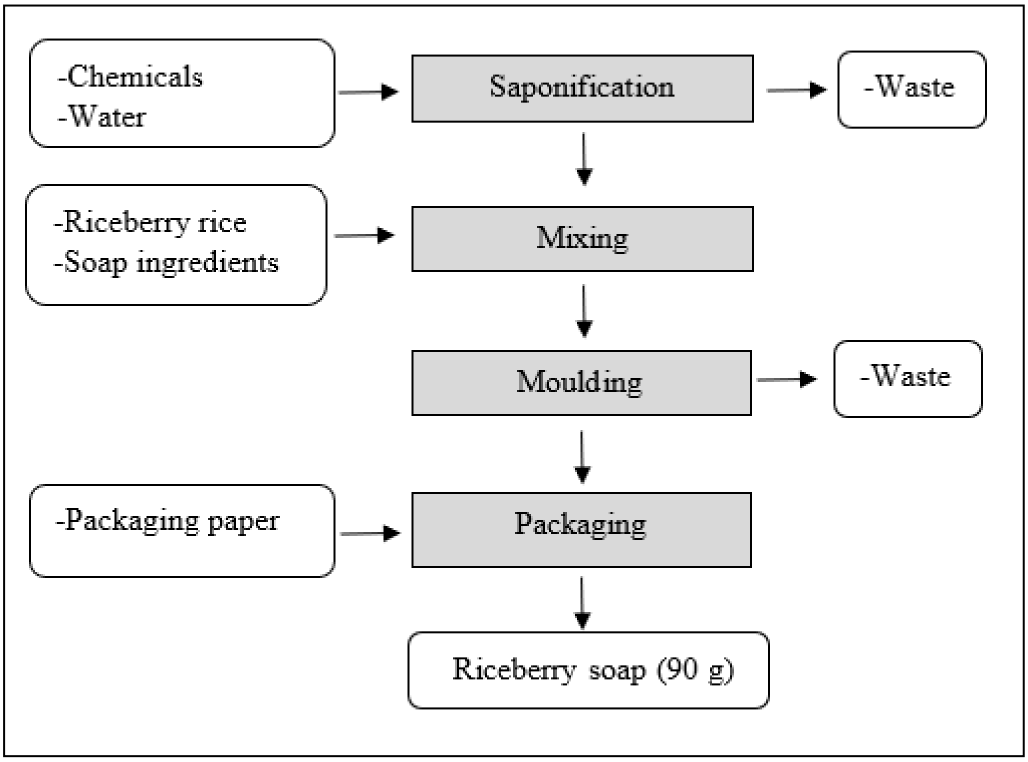

Figure 18 Riceberry soap production process

1.2.2 Riceberry hair conditioner

The production of riceberry hair conditioner consisted of four main stages including raw materials receiving and cleaning, extraction of ingredients, mixing, and packaging as shown in **Figure 19**. In the first stage, all ingredients were cleaned. Then, riceberry and heart-leaved moonseed were extracted by boiling for 2 hrs. For aloe vera, it was blended in a blending machine for fine-grained aloe vera. Later on, all extracted ingredients were mixed with other ingredients (chemicals) in the mixing stage; at this stage, the output product was a liquid riceberry hair conditioner. Finally, the liquid riceberry hair conditioner was filled in a PET bottle, the finished product is 250 ml of riceberry hair conditioner for sale.

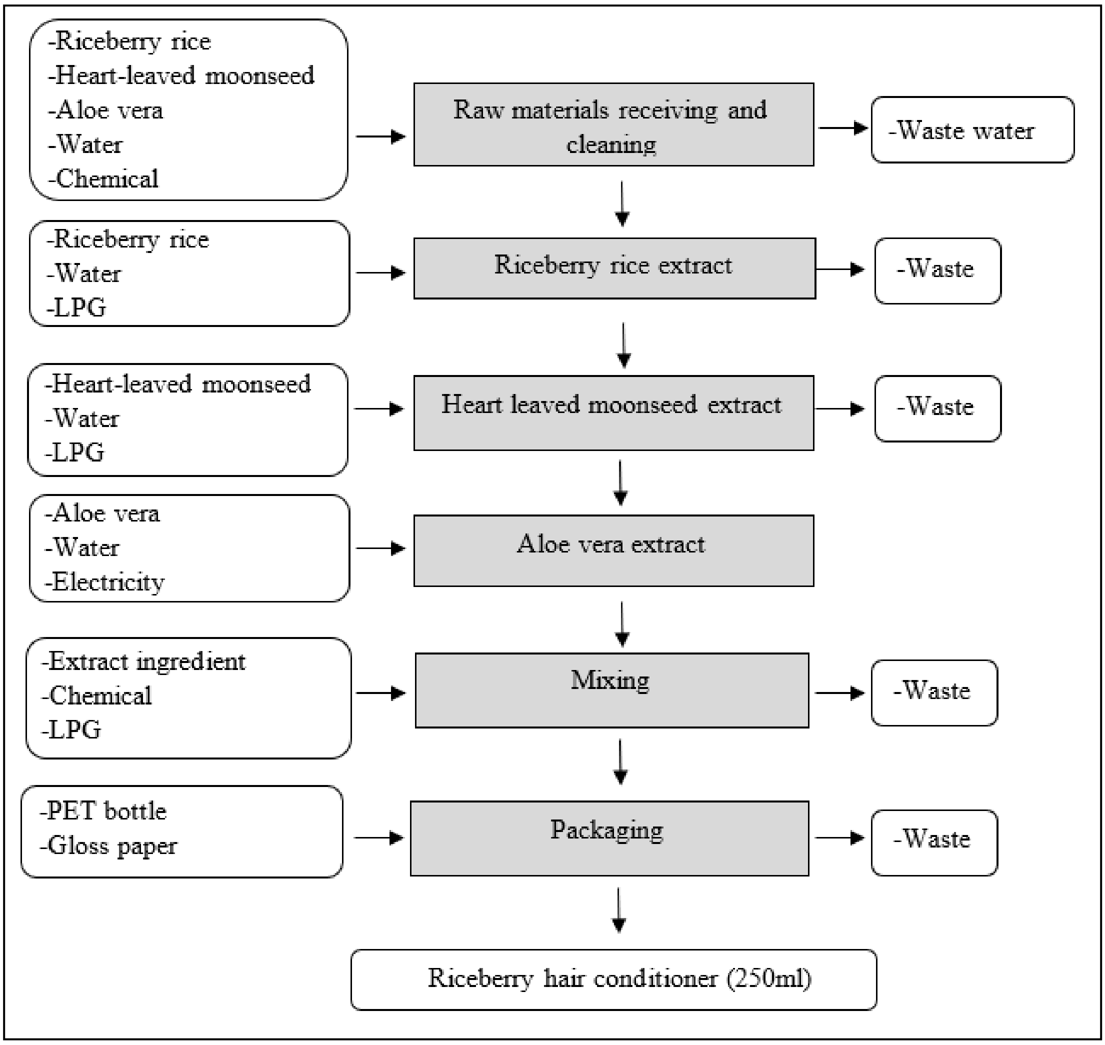

Figure 19 Riceberry hair conditioner production process

1.2.3 Riceberry porridge

The production of riceberry porridge consisted of six main stages including raw materials receiving and cleaning, boiling, freeze-dry process, grinding, mixing, and packaging as shown in **Figure 20.** In the first stage, all ingredients were cleaned. Then, riceberry and vegetables were boiled for 1 hr. After that, all boiled ingredients were freeze-dried and dehydrated in a freeze-dry machine for 3 hrs.; at this stage, the output product was freeze-dried ingredients. The output of freeze-dried riceberry rice was ground in a grinding machine for making a riceberry powder. Later on, all ingredients were mixed in the mixing stage. Finally, riceberry porridge was packed in a Laminated plastic bag (polypropylene and polyethylene terephthalate laminated with aluminum foil), the finished product is 35 g of riceberry porridge for sale.

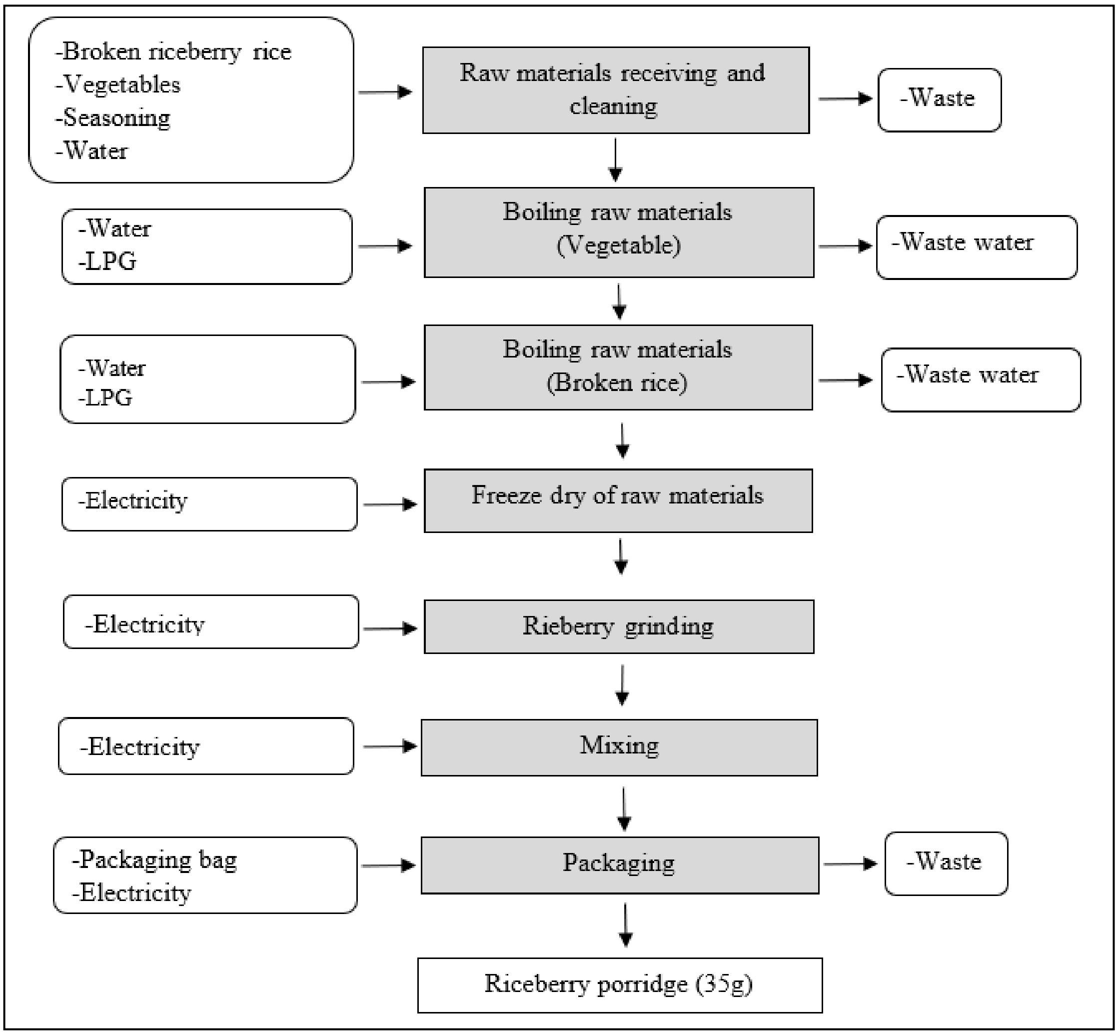

Figure 20 Riceberry porridge production process

1.2.4 Riceberry snack bar

The production of riceberry snack bar consisted of seven stages including riceberry rice cooking, riceberry rice drying, riceberry rice frying, ingredients stir-fried, mixing, molding, and packaging as shown in **Figure 21**. In the first stage, riceberry cooking was cooked in a rice cooker by adding 0.02 L of water. Then, the riceberry rice cooked was dried for 6 hr. by sunlight. After that, riceberry dried was fried. In the next step, other ingredients were stir-fried in the pot. Later on, all ingredients were mixed in the mixing stage. Then, riceberry snack bar was set in molding for 10 mins in the refrigerator. Finally, riceberry snack bar was packed in an oriented polypropylene plastic bag in the packaging process, the output product was 50 g of riceberry snack bar.

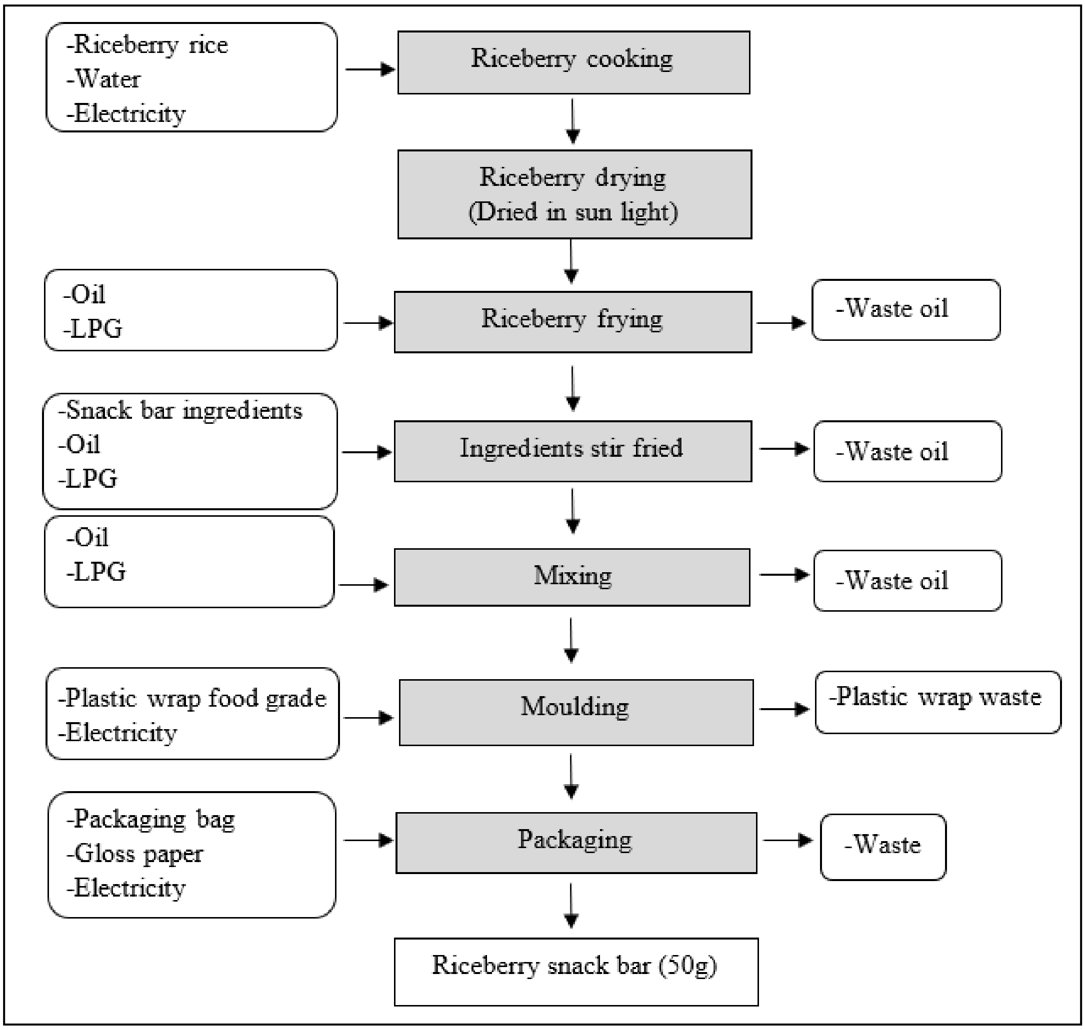

Figure 21 Riceberry snack bar production process

1.3 Functional unit

The functional unit is defined as "product unit" because each riceberry product has a difference size and different function of use. Therefore, to compare between these four products the following units were considered. For riceberry porridge the unit is 35 g, Laminated plastic bag (polypropylene and polyethylene terephthalate laminated with aluminum foil), for riceberry snack bar the unit is 50 g, oriented polypropylene plastic bag, for riceberry soap the unit is 90 g, kraft paper and riceberry hair conditioner the unit is 250 ml, PET bottle.

1.4 Life cycle inventory analysis

1.4.1 The required life cycle inventory data

The required inventory data were identified consisting of the associated inputs (i.e., raw materials, energy, and resources) and outputs (i.e., products, co-products, emissions, and waste) of upstream process (raw materials acquisition stage), core process (production process) and downstream processes (distribution, use and consumption, and disposal stage) based on the annual production in 2019. The overview of the required inventory data was shown in **Table 12.**

Table 12 Required life cycle inventory data

Life cycle stage	Life cycle inventory data	Data source		Reference
		Primary data	Secondary data	
Raw materials acquisition stage				
Raw materials production	The amount of raw materials requirement	✓		Factory annual record, Interview from producers
	Data for raw materials production		✓	Eco-invent database 3.5 and Agri-footprint database 4.0
Packaging production	The amount of packaging requirement	✓		Factory annual record, Interview
	Data for packaging production		✓	Eco-invent database 3.5 and Agri-footprint database 4.0
Production process				
Riceberry processed products production	The number of resources and energy used during the production process including waste and pollution generated.	✓		Factory annual record, Interview
	Data for resources, electricity and energy production		✓	Eco-invent database 3.5 and Agri-footprint database 4.0
Transportation and distribution				
Raw materials	Distance for raw	✓		Factory annual

transportation	materials transportation			record
	Vehicle type and loading capacity	✓		Factory annual record, Interview
	Waste and pollution generated during transportation		✓	Eco-invent database 3.5 and Agri-footprint database 4.0
Products distribution	Distance for products distribution	✓		Factory annual record
	Vehicle type and loading capacity	✓		Factory annual record, Interview
	Waste and pollution generated during transportation		✓	Eco-invent database 3.5 and Agri-footprint database 4.0

		Primary data	Secondary data	
Use and consumption stage				
Use and consumption	The number of resources and energy used during the use and consumption stage including waste and pollution generated.	✓		Instruction manual, Product Category Rules Household Cleaning Products
Disposal stage				
Waste management of packaging	Landfill		✓	Eco-invent database 3.5 and Agri-footprint database 4.0

1.4.2 The life cycle inventory data of each riceberry products

Based on the defined system boundary of riceberry products. Therefore, the life cycle inventory data in each product were identified and input and output data were collected, detailed of the required inventory data for riceberry soap, riceberry hair conditioner, riceberry porridge and riceberry snack bar were shown as follow:

1) Riceberry soap

The amount of all compositions, resources and energy used for making riceberry soap were obtained by interviewing a local producer. The collected data were based on the average values from annual production. Riceberry rice was used as a main ingredient where it was sourced from a nearby riceberry rice field. The associated background data (e.g., secondary data) have been sourced from the LCI national databases, supplemented by the international databased when necessary (for instance, Agri-footprint database (Blonk, 2017 a, b) and Ecoinvent database 3.5 (Ecoinvent Center, 2018). The sources of inventory data are given in **Table 13.**

Table 13 Life cycle inventory data and sources of riceberry soap

Life cycle stage	Process/ materials	Source of LCI data
Raw materials acquisition stage	Riceberry rice (Punpun Organic Farm, Chiangmai)	Product Category Rules Rice Products (PCR) (TGO, 2018) and Agri-footprint database (Blonk, 2017 a, b)
	- Coconut oil - Rice bran oil	Agri-footprint database (Blonk, 2017 a, b)
	- Sodium hydroxide (NaOH) 100% - Essential oil - Kraft paper	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Production process	-Tap water production	
Transportation and distribution stage	-Transport, truck<10t, EURO3, 100%LF, empty return	Agri-footprint database (Blonk, 2017 a, b)
Use stage	Use of Riceberry soap for showering	Product Category Rules Household Cleaning Products (PCR) (TGO, 2017)
Disposal stage	Waste disposal by Sanitary land fill	Ecoinvent database 3.5 (Ecoinvent Center, 2018)

2) Riceberry hair conditioner

The amount of all compositions, resources and energy used for making riceberry hair conditioner were obtained by interviewing a local producer. The collected data were based on the average values from annual production. Riceberry rice was used as a main ingredient where it was sourced from a nearby riceberry rice field. The associated background data (e.g., secondary data) have been sourced from the LCI national databases, supplemented by the international databased when necessary (for instance, Agri-footprint database (Blonk, 2017 a, b) and Ecoinvent database 3.5 (Ecoinvent Center, 2018). The sources of inventory data are given in **Table 14.**

Table 14 Life cycle inventory data and sources of Riceberry hair conditioner

Life cycle stage	Process/ materials	Source of LCI data
Raw materials acquisition stage	Riceberry rice (Wanapun Organic Farm, Khonkaen)	Product Category Rules Rice Products (PCR) (TGO, 2018) and Agri-footprint database (Blonk, 2017 a, b)
	- Heart-leaved moonseed - Aloe vera	Agri-footprint database (Blonk, 2017 a, b)
	- Chemical (Dehydag wax AB) - Dehyquat AC - Preservatives - Fragrance - Cocamide MEA - PET bottle - Gloss paper	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Production process	- Tap water - Gas LPG	
	- Electricity	Electricity Government Authourity of Thailand, (2019) and Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Transportation and distribution stage	Transport, truck<10t, EURO3, 100%LF, empty return	Agri-footprint database (Blonk, 2017 a, b)
Use stage	Use of Riceberry hair conditioner for showering	Product Category Rules Household Cleaning Products (PCR) (TGO, 2017)
Disposal stage	Waste disposal by Sanitary land fill	Ecoinvent database 3.5 (Ecoinvent Center, 2018)

3) Riceberry porridge

The amount of all compositions, resources and energy used for making riceberry porridge were obtained by interviewing a local producer. Broken riceberry rice was used as a main ingredient and it was sourced from the company's riceberry rice field. The collected data were based on the average values from annual production. The associated background data (e.g., secondary data) have been sourced from the LCI national databases, supplemented by the international databased when necessary (for instance, Agri-footprint database (Blonk, 2017 a, b) and Ecoinvent database 3.5 (Ecoinvent Center, 2018)). The sources of inventory data are given in **Table 15.**

Table 15 Life cycle inventory data and sources of riceberry porridge

Life cycle stage	Process/ materials	Source of LCI data
Raw materials acquisition stage	Broken riceberry rice (Kasikam Lavo Thani Co., Ltd., Lopburi)	Product Category Rules Rice Products (PCR) (TGO, 2018) and Agri-footprint database (Blonk, 2017 a, b)
	- Carrot - Mushroom - Celery - Seasoning - Laminated plastic bag (polypropylene and polyethylene terephthalate laminated with aluminum foil)	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Production process	- Tap water - LPG	
	- Electricity	Electricity Government Authority of Thailand, (2019) and Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Transportation and distribution stage	Transport, truck<10t, EURO3, 100%LF, empty return	Agri-footprint database (Blonk, 2017 a, b)
Consumption stage	Drinking water, Electricity	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Disposal stage	Waste disposal by Sanitary land fill	

4) Riceberry snack bar

The amount of all compositions, resources and energy used for making riceberry snack bar were obtained by interviewing a local producer. Riceberry rice was used as a key ingredient, and it was sourced from a local community enterprise. The collected data were based on the average values from annual production. The associated background data (e.g., secondary data) have been sourced from the LCI national databases, supplemented by the international databased when necessary (for instance, Agri-footprint database (Blonk, 2017 a, b) and Eco-invent database 3.5 (Ecoinvent Center, 2018). The sources of inventory data are given in **Table 16.**

Table 16 Life cycle inventory data and sources of riceberry snack bar

Life cycle stage	Process/ materials	Source of LCI data
Raw materials acquisition stage	Riceberry rice (Koh Kok Community Enterprise, Rayong)	Product Category Rules Rice Products (PCR) (TGO, 2018) and Agri-footprint database (Blonk, 2017 a, b)
	-Oat rice -Strawberry -Apricot -Cashew nut -Oil -Honey -Peanut butter -Packaging bag (oriented polypropylene plastic bag) -Plastic wrap food grade	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Production process	-Tap water -LPG	
	-Electricity	Electricity Government Authoурity of Thailand, (2019) and Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Transportation and distribution stage	Transport, truck<10t, EURO3, 100%LF, empty return	Agri-footprint database (Blonk, 2017 a, b)
Consumption stage	-	-
Disposal stage	Waste disposal by Sanitary land fill	Eco-nvent database 3.5 (Ecoinvent Center, 2018)

Table 17 Required life cycle inventory data

Life cycle stage	Life cycle inventory data	Data source		Reference
		Primary data	Secondary data	
Raw materials acquisition stage				
Raw materials production	The amount of raw materials requirement	✓		Factory annual record, Interview from producers
	Data for raw materials production		✓	Eco-invent database 3.5 and Agri-footprint database 4.0
Packaging production	The amount of packaging requirement	✓		Factory annual record, Interview
	Data for packaging production		✓	Eco-invent database 3.5 and Agri-footprint database 4.0
Production process				
Riceberry processed products production	The number of resources and energy used during the production process including waste and pollution generated.	✓		Factory annual record, Interview
	Data for resources, electricity and energy production		✓	Eco-invent database 3.5 and Agri-footprint database 4.0
Transportation and distribution				
Raw materials transportation	Distance for raw materials transportation	✓		Factory annual record
	Vehicle type and loading capacity	✓		Factory annual record, Interview
	Waste and pollution generated during transportation		✓	Eco-invent database 3.5 and Agri-footprint database 4.0
Products distribution	Distance for products distribution	✓		Factory annual record
	Vehicle type and loading capacity	✓		Factory annual record, Interview
	Waste and pollution		✓	Eco-invent

	generated during transportation			database 3.5 and Agri-footprint database 4.0
		Primary data	Secondary data	
Use and consumption stage				
Use and consumption	The number of resources and energy used during the use and consumption stage including waste and pollution generated.	✓		Instruction manual, Product Category Rules Household Cleaning Products
Disposal stage				
Waste management of packaging	Landfill		✓	Eco-invent database 3.5 and Agri-footprint database 4.0

1.4.2 The life cycle inventory data of each Riceberry products

Based on the defined system boundary of riceberry products. Therefore, the life cycle inventory data in each product were identified and input and output data were collected, detailed of the required inventory data for riceberry soap, riceberry hair conditioner, riceberry porridge and riceberry snack bar were shown as follow:

1) Riceberry soap

The amount of all compositions, resources and energy used for making riceberry soap were obtained by interviewing a local producer. The collected data were based on the average values from annual production. Riceberry rice was used as a main ingredient where it was sourced from a nearby riceberry rice field. The associated background data (e.g., secondary data) have been sourced from the LCI national databases, supplemented by the international databased when necessary (for instance, Agri-footprint database (Blonk, 2017 a, b) and Ecoinvent database 3.5 (Ecoinvent Center, 2018). The sources of inventory data are given in **Table 13.**

Table 18 Life cycle inventory data and sources of riceberry soap

Life cycle stage	Process/ materials	Source of LCI data
Raw materials acquisition stage	Riceberry rice (Punpun Organic Farm, Chiangmai)	Product Category Rules Rice Products (PCR) (TGO, 2018) and Agri-footprint database (Blonk, 2017 a, b)
	- Coconut oil - Rice bran oil	Agri-footprint database (Blonk, 2017 a, b)
	- Sodium hydroxide (NaOH) 100% - Essential oil - Kraft paper	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Production process	-Tap water production	
Transportation and distribution stage	-Transport, truck<10t, EURO3, 100%LF, empty return	Agri-footprint database (Blonk, 2017 a, b)
Use stage	Use of Riceberry soap for showering	Product Category Rules Household Cleaning Products (PCR) (TGO, 2017)
Disposal stage	Waste disposal by Sanitary land fill	Ecoinvent database 3.5 (Ecoinvent Center, 2018)

2) Riceberry hair conditioner

The amount of all compositions, resources and energy used for making riceberry hair conditioner were obtained by interviewing a local producer. The collected data were based on the average values from annual production. Riceberry rice was used as a main ingredient where it was sourced from a nearby riceberry rice field. The associated background data (e.g., secondary data) have been sourced from the LCI national databases, supplemented by the international databased when necessary (for instance, Agri-footprint database (Blonk, 2017 a, b) and Ecoinvent database 3.5 (Ecoinvent Center, 2018). The sources of inventory data are given in **Table 14.**

Table 19 Life cycle inventory data and sources of Riceberry hair conditioner

Life cycle stage	Process/ materials	Source of LCI data
Raw materials acquisition stage	Riceberry rice (Wanapun Organic Farm, Khonkaen)	Product Category Rules Rice Products (PCR) (TGO, 2018) and Agri-footprint database (Blonk, 2017 a, b)
	- Heart-leaved moonseed - Aloe vera	Agri-footprint database (Blonk, 2017 a, b)
	- Chemical (Dehydag wax AB) - Dehyquat AC - Preservatives - Fragrance - Cocamide MEA - PET bottle - Gloss paper	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Production process	- Tap water - Gas LPG	
	- Electricity	Electricity Government Authourity of Thailand, (2019) and Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Transportation and distribution stage	Transport, truck<10t, EURO3, 100%LF, empty return	Agri-footprint database (Blonk, 2017 a, b)
Use stage	Use of Riceberry hair conditioner for showering	Product Category Rules Household Cleaning Products (PCR) (TGO, 2017)
Disposal stage	Waste disposal by Sanitary land fill	Ecoinvent database 3.5 (Ecoinvent Center, 2018)

3) Riceberry porridge

The amount of all compositions, resources and energy used for making riceberry porridge were obtained by interviewing a local producer. Broken riceberry rice was used as a main ingredient and it was sourced from the company's riceberry rice field. The collected data were based on the average values from annual production. The associated background data (e.g., secondary data) have been sourced from the LCI national databases, supplemented by the international databased when necessary (for instance, Agri-footprint database (Blonk, 2017 a, b) and Ecoinvent database 3.5 (Ecoinvent Center, 2018)). The sources of inventory data are given in **Table 15.**

Table 20 Life cycle inventory data and sources of riceberry porridge

Life cycle stage	Process/ materials	Source of LCI data
Raw materials acquisition stage	Broken riceberry rice (Kasikam Lavo Thani Co., Ltd., Lopburi)	Product Category Rules Rice Products (PCR) (TGO, 2018) and Agri-footprint database (Blonk, 2017 a, b)
	- Carrot - Mushroom - Celery - Seasoning - Laminated plastic bag (polypropylene and polyethylene terephthalate laminated with aluminum foil)	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Production process	- Tap water - LPG	
	- Electricity	Electricity Government Authority of Thailand, (2019) and Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Transportation and distribution stage	Transport, truck<10t, EURO3, 100%LF, empty return	Agri-footprint database (Blonk, 2017 a, b)
Consumption stage	Drinking water, Electricity	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Disposal stage	Waste disposal by Sanitary land fill	

4) Riceberry snack bar

The amount of all compositions, resources and energy used for making riceberry snack bar were obtained by interviewing a local producer. Riceberry rice was used as a key ingredient, and it was sourced from a local community enterprise. The collected data were based on the average values from annual production. The associated background data (e.g., secondary data) have been sourced from the LCI national databases, supplemented by the international databased when necessary (for instance, Agri-footprint database (Blonk, 2017 a, b) and Eco-invent database 3.5 (Ecoinvent Center, 2018). The sources of inventory data are given in **Table 16.**

Table 21 Life cycle inventory data and sources of riceberry snack bar

Life cycle stage	**Process/ materials**	**Source of LCI data**
Raw materials acquisition stage	Riceberry rice (Koh Kok Community Enterprise, Rayong)	Product Category Rules Rice Products (PCR) (TGO, 2018) and Agri-footprint database (Blonk, 2017 a, b)
	-Oat rice -Strawberry -Apricot -Cashew nut -Oil -Honey -Peanut butter -Packaging bag (oriented polypropylene plastic bag) -Plastic wrap food grade	Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Production process	-Tap water -LPG	
	-Electricity	Electricity Government Authourity of Thailand, (2019) and Ecoinvent database 3.5 (Ecoinvent Center, 2018)
Transportation and distribution stage	Transport, truck<10t, EURO3, 100%LF, empty return	Agri-footprint database (Blonk, 2017 a, b)
Consumption stage	-	-
Disposal stage	Waste disposal by Sanitary land fill	Eco-nvent database 3.5 (Ecoinvent Center, 2018)

1.5 Life Cycle Impact Assessment

After the life cycle inventory analysis was carried out, the result showed the number of raw materials, resources and energy consumption, chemical substance, waste, and pollution generated to the environment throughout the life cycle of products in quantitative terms. To describe the value of the potential environmental impact and show the connection between the product system and the potential environmental impact, the product environmental footprint method referred to the PEF guideline (EC, 2016) was used as the life cycle impact assessment method. The environmental impacts indicators of interest were global warming, human health cancer effect, acidification, freshwater aquatic eco-toxicity, water scarcity, and energy use. This choice has been made according to the widespread use in agricultural LCA studies, allowing for comparison and because focusing on single impacts may mask the shifting of problems between impact categories (Weidema *et al.*, 2008). Consequently, this study included 6 impact indicators listed in the PEF guideline as follows:

The environmental impact indicators can be calculated according to Equation (2).

$$Epj = Qi \times Efij \tag{2}$$

Where as Epj = Environmental impact potential

Qi = Quantity of substance emitted to environment (kg substance j)

Efij = Equivalent factor causing impacts on environment

1.5.1 Global Warming (GW) is an index indicating the potential to cause global warming by considering a gas that absorbs infrared rays in the atmosphere which causes global warming such as methane, carbon dioxide, and nitrous oxide. The unit is expressed as ($kgCO_2e$). The calculation method is shown in Equation (3)

$$\text{Global Warming} = \sum Qi \times GWij \tag{3}$$

Where, Qi is quantity of emission I emitted to environment (kg)

GWij is equivalent of characterization factor of I substance causing environmental impact of j (kg substance equivalent/ kg substance j)

1.5.2 Human Health Cancer Effect (HHC) is an impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin They are related to cancer and expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted. The unit is expressed as (CTUh). The calculation method is shown in Equation (4)

$$\text{Human health cancer effect} = \sum Qi \times HHCij \tag{4}$$

Where, Qi is quantity of emission I emitted to environment (kg)

HHCij is equivalent of characterization factor of I substance causing environmental impact of j (kg substance equivalent/ kg substance j)

1.5.3 Acidification (AC) is an impact indicator that characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. The unit is expressed as (mol H^{+}e). The calculation method is shown in Equation (5)

$$\text{Acidification} = \sum Qi \times Acij \tag{5}$$

Where, Qi is quantity of emission I emitted to environment (kg)

Acij is equivalent of characterization factor of I substance causing environmental impact of j (kg substance equivalent/ kg substance j)

1.5.4 Freshwater aquatic eco-toxicity (FWAE) is an expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted. The unit is expressed as (CTUe). The calculation method is shown in Equation (6)

$$\text{Freshwater aquatic eco-toxicity} = \sum Qi \times FWAEij \tag{6}$$

Where, Qi is quantity of emission I emitted to environment (kg)

FWAEij is equivalent of characterization factor of I substance causing environmental impact of j (kg substance equivalent/ kg substance j)

1.5.5 Water scarcity (WS) is an impact indicator expressing a Relative Available Water Remaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met. The unit is expressed as (m^3depriv). The calculation method is shown in Equation (7)

$$\text{Water scarcity} = \sum Qi \times Wsij \tag{7}$$

Where, Qi is quantity of emission I emitted to environment (kg)

Wsij is equivalent of characterization factor of I substance causing environmental impact of j (kg substance equivalent/ kg substance j)

1.5.6 Energy use (EU) is an impact indicator expressing the Abiotic resource depletion fossil fuels (ADP-fossil); based on lower heating value ADP for energy carriers. The unit is expressed as (MJ). The calculation method is shown in Equation (8)

$$\text{Energy use} = \sum Qi \times Euij \tag{8}$$

Where, Qi is quantity of emission I emitted to environment (kg)

Euij is equivalent of characterization factor of I substance causing environmental impact of j (kg substance equivalent/ kg substance j)

1.6 Interpretation

This stage of LCA used the obtained results from the life cycle inventory and the life cycle impact assessment to analyse and interpret the results of the environmental impact for each studied product. The outcome of the interpretation phase is a set of conclusions and recommendations that review from the result of LCA. The objective of this interpretation phase is (1) to assess the environmental performances of riceberry processed products (2) to identify the source of the environmental issue which leads to effective environmental impact improvements of each riceberry product.

2. Eco-efficiency assessment

2.1 Goal and scope

The goal of this study was (1) to assess the economic performances of riceberry processed products, and (2) to evaluate the integration of environmental and economic performances, expressed as the eco-efficiency values of riceberry processed products to provide the decision supporting information to improve environmental and economic performances for private companies and to suggest which products should be further developed and promoted to move towards sustainability for policy makers.

2.2 Products system value assessment

The value of the product systems is based on the financial values of the products. In this study, the selling price in the market was used as the product system value. The selling price of studied products in the market can be used to reflect the production cost and the profit to producers. At the same time, the selling price also reflects the business model and quality of products both in terms of the physical quality and the beauty of the product's packaging because packing is a factor affecting costs. It also causes a price increase of the product. The manufacturers will bear the additional costs of packing, and if these costs can provide the desired advantages by reflecting on prices, it will not cause any problem. However, packing should fulfill all its functions for consumers are willing to pay a high price (Atagan *et al.*, 2013).

2.3 Qualification of eco-efficiency

The eco-efficiency indicator was calculated by dividing product system value (selling price) with selected environmental impacts indicators, as shown in Equation (9)

$$\text{Eco-efficiency} = \text{Selling price} / \text{Environmental impacts indicator} \tag{9}$$

This equation provides a ratio of the selling price per unit of environmental impact. The higher the numerator value, means higher economic performance leading to higher eco-efficiency. Similarly, a lower denominator value means lower environmental impacts are also leading to higher eco-efficiency value.

3. Integration of LCA and Eco-efficiency

In this stage, LCA and eco-efficiency will be combined for the integration of environmental and economic performances. In this stage, the integration for product improvement will follow step by step as follows:

3.1 LCIA results

In this stage, the contribution analysis results of the LCIA were performed to identify the hotspots of each riceberry product linking to the hotspots identified, and the possible options for improving the environmental performances were proposed.

3.2 Product improvement

In addition to the improvements of environmental performance, and the improvement of economic performances, especially the product system value, were proposed by increasing the selling price.

3.3 Comparative eco-efficiency values of original and new products

In this stage, the eco-efficiency values were compared between original and new products (applying the improvement options), expressed as the percentage of life cycle impact decreasing and eco-efficiency value increasing.

RESULTS AND DISCUSSION

RESULTS

1. Life cycle inventory analysis result

1.1 The inventory data analysis result of riceberry soap

1.1.1 The inventory data analysis results of the raw materials acquisition stage

The main ingredients for soap production have consisted of coconut oil, the main composition for making riceberry soap, and Sodium hydroxide (NaOH) 100% which use as the main ingredients for the saponification process, while riceberry rice was used as an additive due to small composition in the riceberry soap recipe. Moreover, kraft paper was used as the packaging for riceberry soap as representative of hand-made soap. The number of inputs and outputs of inventory data obtained was calculated per 90 g of riceberry soap production as shown in **Table 17.**

Table 22 LCI data of raw materials acquisition for riceberry soap

Life cycle stage	Unit	Quantity		Unit	Quantity
Raw material acquisition					
Inputs			*Outputs*		
Riceberry rice	kg	0.0028	Riceberry rice	kg	0.0028
Coconut oil	L	0.0563	Coconut oil	L	0.0563
Sodium hydroxide (NaOH) 100%	L	0.0122	Sodium hydroxide (NaOH) 100%	L	0.0122
Essential oil	L	0.0008	Essential oil,	L	0.0008
Rice bran oil	L	0.0188	Rice bran oil	L	0.0188
Kraft paper	kg	0.0050	Kraft paper	kg	0.0050
Sticker	kg	0.0050	Sticker	kg	0.0050

1.1.2 The inventory data analysis results of production process

The production process of riceberry soap is a cold. Therefore, the energy and resources used in this production process were only tap water use for the saponification process with NaOH 100%. The amount of tap water and other ingredients used were calculated per 90 g of riceberry soap production as shown in **Table 18.**

Table 23 LCI data of production process for riceberry soap

Life cycle stage	Unit	Quantity		Unit	Quantity
Production process					
1) Saponification					
Inputs			*Outputs*		
Sodium hydroxide (NaOH) 100%	L	0.0122	Mixing of sodium hydroxide (NaOH) 100% and water	L	0.0407
Water	L	0.0285			
2) Mixing					
Inputs			*Outputs*		
Mixing of sodium hydroxide (NaOH) 100% and water	L	0.0407	Soap liquid	L	0.1193
Riceberry	kg	0.0028			
Coconut oil	L	0.0563			
Essential oil	L	0.0008			
Rice bran oil	L	0.0188			
3) Molding					
Inputs			*Outputs*		
Soap liquid	L	0.1193	Riceberry soap (90 g)	kg	0.0900
			Waste of soap (cut-off)	kg	0.0293
4) Packaging					
Inputs			*Outputs*		
Riceberry soap (90 g)	kg	0.0900	Riceberry soap in packaging (90 g)	piece	1

Kraft paper	kg	0.0050
Gloss paper	kg	0.0050

1.1.3 The inventory data analysis results of transportation and distribution stage

The transportation data of raw materials were obtained from the producers by considering the distance from the ingredients shop located in Chiangmai city to the Punpun organic farm (production factory). The distance is varied from 20-72 km, depending on the shop's location. The background data of transportation was based on the vehicle type of truck with a loading capacity of 10 tons 100% full load and empty return (Durlinger *et al.*, 2017). Similarly, the distribution of riceberry soap was the same distance. For the distribution, the transportation was based on the vehicle type of truck with a loading capacity of 10 tons 100% full load and empty return (Durlinger *et al.*, 2017). All data on transportation and distribution were shown in **Table 19.**

Table 24 LCI data of transportation and distribution stage for riceberry soap

Life cycle stage	Vehicle	Route	Distance (km)	Loading capacity (Ton)	Return transportation
Transportation of raw materials	Pickup truck	Average distance from shop to factory	20-72	0.5	0
Distribution of products	Pickup truck	Average distance from factory to retail store	58	0.5	0

1.1.4 The inventory data of use stage

For the use phase, it was calculated from one time of body showering which required 30 L of water and water treatment and 2 g of riceberry soap. However, the use stage was not considered in this study because it would be the same for riceberry soap.

1.1.5 The inventory data analysis results of disposal stage

For the disposal stage, it was calculated by considering the packaging materials (kraft paper) and sticker (gloss paper) generated after the use. All waste generated was assumed to be landfilled.

1.2 The inventory data analysis of riceberry hair conditioner

1.2.1 The inventory data analysis results of the raw material acquisition stage

The main ingredients for hair conditioner production consisted of chemical ingredients (Dehydax wax AB, dehyquat AC, cocamide MEA, preservative and fragrance) which is the main composition of chemicals used for making hair conditioner. However, hair conditioner needs the additive from natural ingredients. For instance, riceberry rice contains Vitamin E and antioxidants to support the healthy scalp and hair for a shiny black hair look, aloe vera and heart-leaved moonseed were used as an herbal additive for slow down the graying of hair, and hair loss. The number of inputs and outputs of inventory data obtained were calculated per 250 ml. of riceberry hair conditioner production as shown in **Table 20.**

Table 25 LCI data of raw materials acquisition for riceberry hair conditioner

Life cycle stage	**Unit**	**Quantity**		**Unit**	**Quantity**
Raw material acquisition					
Inputs			*Outputs*		
Riceberry rice	kg	0.0200	Riceberry rice	kg	0.0200
Heart-leaved moonseed	kg	0.0200	Heart-leaved moonseed	kg	0.0200
Aloe vera	kg	0.0300	Aloe vera	kg	0.0300
Chemical (Dehydag wax AB)	kg	0.1070	Chemical (Dehydag wax AB)	kg	0.1070
Dehyquat AC	kg	0.0267	Dehyquat AC	kg	0.0267
Preservatives	kg	0.0133	Preservatives	kg	0.0133
Fragrance	kg	0.0013	Fragrance	kg	0.0013
Cocamide MEA	kg	0.0120	Cocamide MEA	kg	0.0120
PET Bottle	kg	0.0300	PET Bottle	kg	0.0300
Gloss paper	kg	0.0010	Gloss paper	kg	0.0010

1.2.2 The inventory data analysis results of production process

The energy and resources used in this production process required tap water, gas LPG, and electricity consumption in each stage of the production process. The amount of energy and resources used were then calculated per 250ml. of riceberry hair conditioner production as shown in **Table 21.**

Table 26 LCI data of production process for riceberry hair conditioner

Life cycle stage	**Unit**	**Quantity**		**Unit**	**Quantity**
Production process					
1) Raw materials receiving and cleaning					
Inputs			*Outputs*		
Riceberry rice	kg	0.0200	Riceberry rice	kg	0.0200
Heart-leaved moonseed	kg	0.0200	Heart-leaved moonseed	kg	0.0200
Aloe vera	kg	0.0300	Aloe vera	kg	0.0300
Water	L	1.00	Wastewater	L	1.00
2) Extraction of Riceberry					
Inputs			*Outputs*		
Riceberry rice	kg	0.0200	Riceberry rice extracted water	L	0.0427
Water	L	0.06			
Resource and supporting materials					
Gas LPG	MJ	2.45			
3) Extraction of heart-leaved moonseed					
Inputs			*Outputs*		
Heart-leaved moonseed	kg	0.0200	Heart-leaved moonseed extracted water	L	0.0320
Water	L	0.0600			
Gas LPG	MJ	2.45			
4) Extraction of aloe vera					

Inputs			*Outputs*		
Aloe vera	kg	0.0320	Aloe vera extracted water	kg	0.0320
Electricity	kWh	0.0050			
5) Mixing					
Inputs			*Outputs*		
Extracted ingredients	kg	0.1067	Hair conditioner cream	kg	0.2670
Chemical (Dehydag wax AB)	kg	0.1070			
Dehyquat AC	kg	0.0267			
Preservatives	kg	0.0133			
Fragrance	kg	0.0013			
Cocamide MEA	kg	0.0120			
Resource and supporting materials					
Gas LPG	MJ	2.45			
6) Packaging					
Inputs			*Outputs*		
Hair conditioner cream	kg	0.2670	Riceberry hair conditioner (250 ml)	Piece	1
PET Bottle	kg	0.0300			
Gloss paper	kg	0.0010			

1.2.3 The inventory data analysis results of transportation and distribution stage

The transportation data of raw materials were obtained from the producers by considering the distance from the ingredients shop located in Bangkok to Wanapun Organic Farm in Khonkaen (Production factory). The distance is 470 km from the shop's location. The background data of transportation was based on the vehicle type of truck with a loading capacity of 10 tons 100% full load and empty return (Durlinger *et al*., 2017). In a similar way, the distribution of riceberry hair conditioner was obtained from the producers by considering the distance from Wanapun Organic Farm in Khonkaen (Production factory) to the retail store in Iconsiam Bangkok. The distance is 495 km. The background data of distribution was also based on the vehicle type of truck with a loading capacity of 10 tons 100% full load and empty return (Durlinger *et al*., All data on transportation and distribution were shown in **Table 22.**

Table 27 LCI data of transportation stage for riceberry hair conditioner

Life cycle stage	Vehicle	Route	Distance (km)	Loading capacity (Ton)	Return transportation
Transportation of raw materials	Pickup truck	Average distance from shop to factory	470	0.5	0
Distribution of products	Pickup truck	Average distance from factory to retail store	495	0.5	0

1.2.4 The inventory data analysis results of use stage

For the use phase, it was calculated from one time of body showering which required 30 L of water and water treatment and 5 ml. of riceberry hair conditioner. However, the use stage was not considered in this study because it would be the same for each time of showering by using riceberry hair conditioner.

1.2.5 The inventory data analysis results of the disposal stage

For the disposal stage, it was calculated by considering the packaging materials (PET bottle) generated after the use stage. All waste generated was assumed to be landfilled.

1.3 The inventory data analysis of riceberry porridge

1.3.1 The inventory data analysis results of the raw materials acquisition stage

The main ingredients for riceberry porridge production consisted of porridge ingredients (broken riceberry rice, and seasoning), while carrot, shiitake mushroom, and celery were used as vegetable additive for increasing more nutrients to riceberry porridge product and to increase more value-added. Moreover, a Laminated plastic bags (polypropylene and polyethylene terephthalate laminated with aluminum foil) were used as the packaging bag material. The number of inputs and outputs of inventory data obtained were calculated per 35g of riceberry porridge production as shown in **Table 23.**

Table 28 LCI data of the raw materials acquisition for riceberry porridge

Life cycle stage	Unit	Quantity		Unit	Quantity
Raw materials Acquisition					
Inputs			*Outputs*		
Broken riceberry rice	kg	0.0375	Broken riceberry rice	kg	0.0375
Carrot	kg	0.0250	Carrot	kg	0.0250
Shiitake Mushroom	kg	0.0250	Shiitake Mushroom	kg	0.0250
Celery	kg	0.0250	Celery	kg	0.0250
Seasoning	kg	0.0025	Seasoning	kg	0.0025
Packaging bag	kg	0.0100	Packaging bag	kg	0.0100

1.3.2 The inventory data analysis results of production process

The energy and resources used in the production process of riceberry porridge production required tap water, LPG gas, and electricity consumption. The amount of energy and resources used were then calculated per 35 g of riceberry porridge production as shown in **Table 24.**

Table 29 LCI data of production process for riceberry porridge

Life cycle stage	Unit	Quantity		Unit	Quantity
Production process					
1) Raw materials receiving and cleaning					
Inputs			*Outputs*		
Broken riceberry rice	kg	0.0375	Broken riceberry rice	kg	0.0375
Carrot	kg	0.0250	Carrot	kg	0.0250
Shiitake Mushroom	kg	0.0250	Shiitake Mushroom	kg	0.0250
Celery	kg	0.0250	Celery	kg	0.0250
Water	L	0.1500	Wastewater	L	0.1500
2) Boiling the raw materials (Vegetables)					

Inputs			Outputs		
Carrot	kg	0.0250	Boiled Carrot	kg	0.0250
Shiitake Mushroom	kg	0.0250	Boiled Mushroom	kg	0.0250
			Wastewater	L	0.1500
Resource and supporting materials					
Water	L	0.1500			
LPG Gas	MJ	0.0100			
3) Boiling raw materials (Broken rice)					
Inputs			*Outputs*		
Broken riceberry rice	kg	0.0375	Riceberry with seasoning	kg	0.0375
Seasoning	kg	0.0010	Wastewater	L	0.1500
Resource and supporting materials					
Water	L	0.1500			
LPG Gas	MJ	0.0100			
4) Freeze dry of raw materials					
Inputs			*Outputs*		
Riceberry with seasoning	kg	0.0375	Freeze dried riceberry	kg	0.0116
Boiled Carrot	kg	0.0250	Freeze dried Carrot	kg	0.0078
Boiled Mushroom	kg	0.0250	Freeze dried Mushroom	kg	0.0078
Celery	kg	0.0250	Freeze dried Celery	kg	0.0078
			Freeze dried waste	kg	0.0010
Resource and supporting materials					
Electricity for freeze dry machine	kWh	0.0293			
5) Riceberry grinding					
Inputs			*Outputs*		

Freeze dried riceberry	kg	0.0116	Freeze dried riceberry grinded	kg	0.0116
Resource and supporting materials					
Electricity for milling machine	kWh	0.0070			
6) Mixing					
Inputs			*Outputs*		
Freeze dried riceberry grinded	kg	0.0116	Mixing ingredients for porridge	kg	0.0350
Freeze dried carrot	kg	0.0078			
Freeze dried Mushroom	kg	0.0078			
Freeze dried celery	kg	0.0078			
Resource and supporting materials					
Electricity for mixing machine	kWh	0.0004			
Electricity for weighing machine	kWh	0.0004			
7) Packaging					
Inputs			*Outputs*		
Mixing ingredient for porridge	kg	0.0350	Riceberry porridge in packaging	piece	1
Packaging bag	kg	0.0100			
Electricity for packaging machine	kWh	0.0028			

1.3.2 The inventory data analysis results of transportation and distribution stage

The transportation data of raw materials were obtained from the producers by considering the distance from the ingredients shop in Lopburi to the Lawo Thani Agricultural Network Learning Center in Lopburi (Production factory). The distance varied from 4-14 km depending on the shop's location. The background data of transportation was based on the vehicle type of truck with a loading capacity of 10 tons 100% full load and empty return (Durlinger *et al*., 2017). Because the distribution of products was not considered, this riceberry porridge product was sold at the retail store in front of the production factory. All data on transportation and distribution were shown in **Table 25.**

Table 30 LCI data of distribution stage for riceberry porridge

Life cycle stage	Vehicle	Route	Distance (km)	Loading capacity (Ton)	Return transportation
Transportation of raw materials	Pickup truck	Average distance from shop to factory	4-14	0.5	0
Distribution of products	Pickup truck	Average distance from factory to retail store	0	0.5	0

1.3.3 The inventory data analysis results of consumption stage

In the consumption stage, riceberry porridge was consumed following the instruction guides of the product by using 100 ml of boiled water for 3 minutes before consumption.

1.3.4 The inventory data analysis results of the disposal stage

For the disposal stage, it was calculated by considering the packaging materials Laminated plastic bag (polypropylene and polyethylene terephthalate laminated with aluminum foil), generated after the consumption stage. All waste generated was assumed to be landfilled.

1.4 The inventory data analysis of riceberry snack bar

1.4.1 The inventory data analysis results of the raw materials acquisition stage.

The main ingredient of riceberry snack bar production was riceberry rice, while the other ingredients were used as an additive to improve the taste, texture and nutrition properties to the snack bar which consist of oat rice, strawberry, apricot, cashew nut, honey, and peanut butter. Moreover, riceberry snack bar used an OPP bag as packaging materials. The number of inputs and outputs of inventory data that were obtained were calculated per 50 g of riceberry snack bar production as shown in **Table 26**.

Table 31 LCI data of the raw materials acquisition stage for riceberry snack bar

Life cycle stage	Unit	Quantity		Unit	Quantity
Raw materials acquisition					
Inputs			*Outputs*		
Riceberry rice	kg	0.0136	Riceberry rice	kg	0.0136
Oat rice	kg	0.0015	Oat rice	kg	0.0015
Strawberry	kg	0.0035	Strawberry	kg	0.0035
Apricot	kg	0.0035	Apricot	kg	0.0035
Cashew nut	kg	0.0035	Cashew nut	kg	0.0035
Oil	L	0.0050	Oil	L	0.0050
Honey	L	0.0105	Honey	L	0.0105
Peanut butter	L	0.0105	Peanut butter	L	0.0105
Packaging bag (OPP)	kg	0.0025	Packaging bag (OPP)	kg	0.0025
Plastic wrap food grade	kg	0.0010	Plastic wrap food grade	kg	0.0010

1.4.2 Inventory analysis of production process

The energy and resources used in the production process of riceberry snack bar production required tap water, gas LPG and electricity consumption. The amount of energy and resources used were then calculated per 50g. of riceberry snack bar production as shown in **Table 27.**

Table 32 LCI data of the production process for riceberry snack bar

Life cycle stage	Unit	Quantity		Unit	Quantity
Production process					
1) Riceberry cooking					
Inputs			*Outputs*		
Riceberry	kg	0.0136	Cooked riceberry	kg	0.0136
Resource and supporting materials					
Water	L	0.0200			
Electricity (for rice cooker)	kWh	0.0039			
2) Riceberry sun drying					
Inputs			*Outputs*		
Cooked riceberry	kg	0.0136	Dried riceberry	kg	0.0136
3) Riceberry frying					
Inputs			*Outputs*		
Dried riceberry	kg	0.0136	Fried riceberry	kg	0.0170
			Waste oil	L	0.0050
Resource and supporting materials					
Cooking oil	L	0.0050			
LPG	MJ	0.0100			
4) Ingredients stir fried					

Inputs			Outputs		
Oat rice	kg	0.0015	Fried oat rice	kg	0.0015
Strawberry	kg	0.0035	Fried strawberry	kg	0.0035
Apricot	kg	0.0035	Fried apricot	kg	0.0035
Cashew nut	kg	0.0035	Fried cashew nut	kg	0.0035
Resource and supporting materials					
Cooking oil	L	0.0001			
LPG	MJ	0.0100			
5) Mixing					
Inputs			*Outputs*		
Fried riceberry	kg	0.0170	Mixed ingredients	kg	0.0500
Fried oat rice	kg	0.0015			
Fried strawberry	kg	0.0035			
Fried apricot	kg	0.0035			
Fried cashew nut	kg	0.0035			
Honey	L	0.0105			
Peanut butter	L	0.0105			
Resource and supporting materials					
Cooking oil	L	0.0010			
LPG	MJ	0.0100			

6) Molding					
Inputs			*Outputs*		
Mixed ingredients	kg	0.0500	Riceberry snack bar	kg	0.0500
Plastic wrap food grade	kg	0.0010	Wasted wrapping plastic	kg	0.0010
Resource and supporting materials					
Electricity (for refrigerator)	kWh	0.0010			
7) Packaging					
Inputs			*Outputs*		
Riceberry snack bar	kg	0.0500	Riceberry snack bar in pack	Piece	1
Plastic bag (OPP)	kg	0.0025			
Resource and supporting materials					
Electricity (for sealing machine)	kWh	0.0010			

1.4.3 The inventory data analysis results of the transportation and distribution stage.

The transportation data of the raw materials were obtained from the producers by considering the distance from the ingredients shop to Koh Kok Community Enterprise in Rayong (Production factory). The distance was 10 km from the shop's location The background data of transportation was based on the vehicle type of truck with a loading capacity of 10 tons 100% full load and empty return (Durlinger *et al*., 2017) The distribution of riceberry snack bar were obtained from the producers by considering the distance from Koh Kok Community Enterprise (Production factory) to the retail store in Rayong. The distance is 10 km. from the production factory. The background data of transportation was based on the vehicle type of truck with a loading capacity of 10 tons 100% full load and empty return (Durlinger *et al*., 2017). All data on transportation and distribution were shown in **Table 28.**

Table 33 LCI data of distribution stage for riceberry snack bar

Life cycle stage	Vehicle	Route	Distance (km)	Loading capacity (Ton)	Return transportation
Transportation of the raw materials	Pickup truck	Average distan from ingredien shop to factory	10	0.5	0
Distribution of the products	Pickup truck	Average distan from factory to retail store	10	0.5	0

1.4.4 Consumption stage

In the consumption stage of the riceberry snack bar, it does not require any resources and energy used during this consumption stage.

1.4.5 The inventory data analysis results of the disposal stage

For the disposal stage, it was calculated by considering the packaging materials (OPP) generated after the consumption stage. All waste generated was assumed to be landfilled.

2. Life Cycle Impacts Assessment (LCIA) results

2.1 LCIA results of riceberry products contribution

The overall LCIA result of the 4 riceberry products was shown in **Table 29**. As can be seen, for non-food products, riceberry hair conditioner has considerably higher impacts than the other products in only the global warming indicator due to high impact of dehydag wax ab, and riceberry rice while riceberry soap has considerably higher impacts than the other products in human health cancer effects, acidification, and freshwater aquatic eco-toxicity indicators, largely due to impacts of raw materials are higher for the riceberry soap because of the coconut oil and rice bran oil production. For food products, riceberry porridge had the highest impacts the on environment in water scarcity and energy use indicators, largely due to the electricity consumption in the manufacturing process, while riceberry snack bar has lower impacts in all indicators. These results are discussed in more detail for each impact in the following sections, the impact contribution for each riceberry product was explained in the **Figure. 22-27** via the result of impact contribution in each stage of the system boundary (cradle to grave). Moreover, the result of impact contribution indicated that the raw materials acquisition stage was the key hotspot significantly contributing to more than 50% of all impacts for all studied products. Therefore, the result of impacts contribution from raw materials used in each riceberry product was explained via **Figure. 28-31.**

Table 34 LCIA result of original riceberry products

Impact indicators	Riceberry soap	Riceberry hair conditioning	Riceberry porridge	Riceberry snack bar
Global warming ($kgCO_2e$)	4.34E-01	8.13E-01	5.90E-01	2.74E-01
Human health cancer effects (CTUh)	1.33E-08	4.86E-09	3.46E-09	3.18E-09
Acidification (mol H^+e)	3.66E-03	3.04E-03	1.95E-03	1.38E-03
Fresh water aquatic eco-toxicity (CTUe)	7.12E+00	6.23E-01	1.12E+00	2.58E+00
Water scarcity (m^3depriv)	3.97E-01	5.85E-01	1.07E+00	8.40E-01
Energy use (MJ)	3.21E+00	6.36E+00	3.69E+00	2.55E+00

Figure 22 showed the comparative LCIA results of products studied in the global warming indicator. The LCIA result of riceberry products in GW indicator showed that all products studied had the key hotspot at the raw materials acquisition stage. For non-food products, riceberry soap had the impacts on global warming indicator equal to 4.34E-01 kgCO_2 e with the impact contribution causing from the raw materials acquisition stage (99%), and other stages less than 1%, while riceberry hair conditioner had the impacts on global warming indicator equal to 8.13E-01 kgCO_2e with the impact contribution causing from raw materials acquisition stage (83%), production process (11%), transportation (5%) and other stages less than 1%. For food products, riceberry porridge had the impacts on the global warming indicator equal to 5.90E-01 kgCO_2e with the impact contribution caused from the raw materials acquisition stage (65%) follow by the production process (22%), and use stage (12%) and other stages less than 1%, while riceberry snack bar had the impacts on the global warming indicator equal to 2.74E-01 kgCO_2e. with the impact contribution caused from raw materials acquisition stage (86%), followed by the production process (22%), and other stages less than 1%.

Comparing various riceberry products, it was found that riceberry hair conditioner had the highest impact on the global warming indicators (8.13E-01 kgCO_2e). The key hotspot caused significant impact was associated with the raw materials acquisition stage (83%) resulted from the production of Dehydag WAX AB (46%), PET bottle production (16%), and riceberry rice farming (26%), The lowest impact on global warming indicator was riceberry snack bar due mainly to lower composition of ingredients and low impacts of ingredients used for making riceberry snack bar. However, the key hotspot causing significant impacts was also associated with the raw materials acquisition stage (86%) resulting from the production of riceberry rice especially in the farming stage (50%), and other ingredients ranging from 1 to 10%.

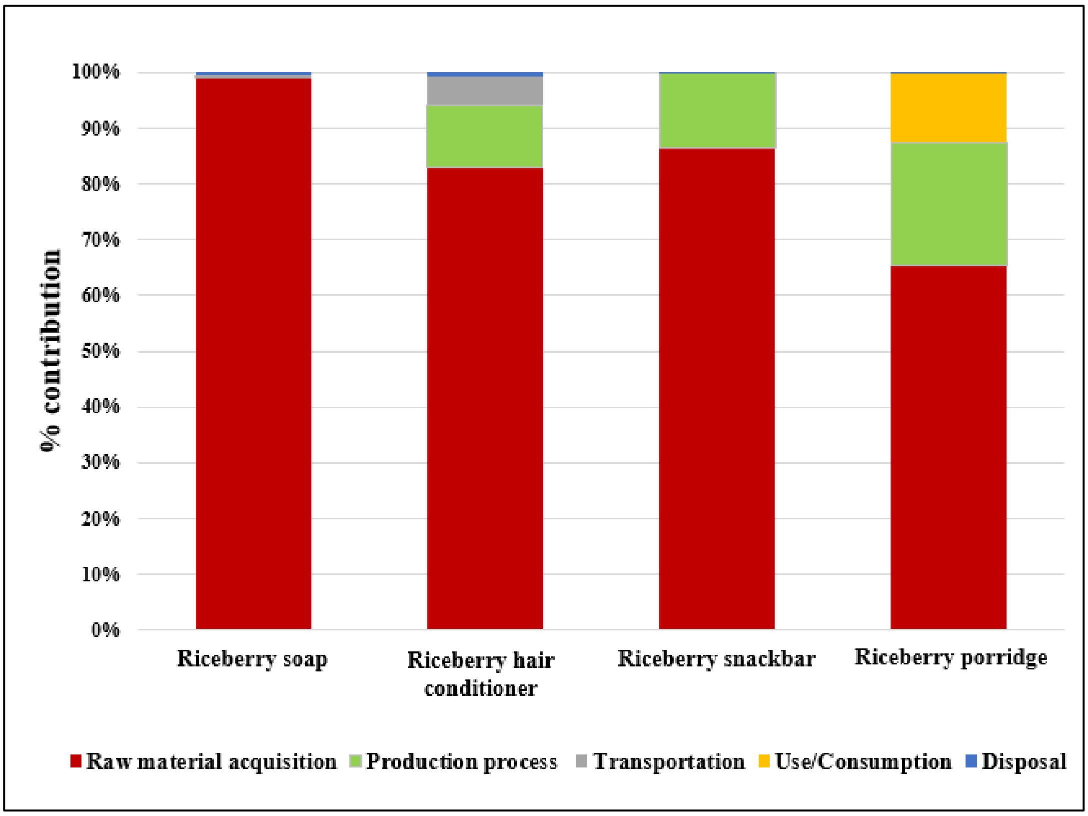

Figure 22 LCA contribution results on global warming indicators

Figure 23 showed the comparative LCIA results of products studied in the human health cancer effects indicator. The LCIA result of riceberry products in human health cancer effects indicator showed that all products studied had the key hotspot at the raw materials acquisition stage. For non-food products, riceberry soap had the impacts on human health cancer effects indicator equal 1.33E-08 CTUh with the impact contribution causing from the raw materials acquisition stage equal 99% and other stages less than 1%, while riceberry hair conditioners had the impacts on human health cancer effects indicator equal to 4.86E-09 CTUh with the impact contribution causing from the raw materials acquisition stage (91%), production process (8%), transportation (1%) and other stages less than 1%. For food products, riceberry porridge had the impacts on human health cancer effects indicator equal 3.46E-09 CTUh with the impact contribution causing from the raw materials acquisition stage (53%) followed by the production process (28%) and use stage (19%) and other stages less than 1%, while riceberry snack bar had the impacts on human health cancer effects indicator equal to 3.18 E-09 CTUh with the impact contribution caused from the raw materials acquisition stage (91%), followed by the production process (9%), and other stages less than 1%.

Comparing various riceberry products, it was found that riceberry soap had the highest impact on human health cancer effects indicator (1.33E-08 CTUh) The key hotspot causing significant impacts was associated with the raw materials acquisition stage (99%) resulting from the production of coconut oil (75%) especially the crude coconut oil production, rice bran oil (12%) and riceberry rice (6%). The lowest impact on human health cancer effects indicator was the riceberry snack bar (3.18 E-09 CTUh). However, it is very interesting that the main ingredients causing human health cancer effects impacts indicator were largely due to peanut butter (42%) while the other ingredients ranging from only 1-13%.

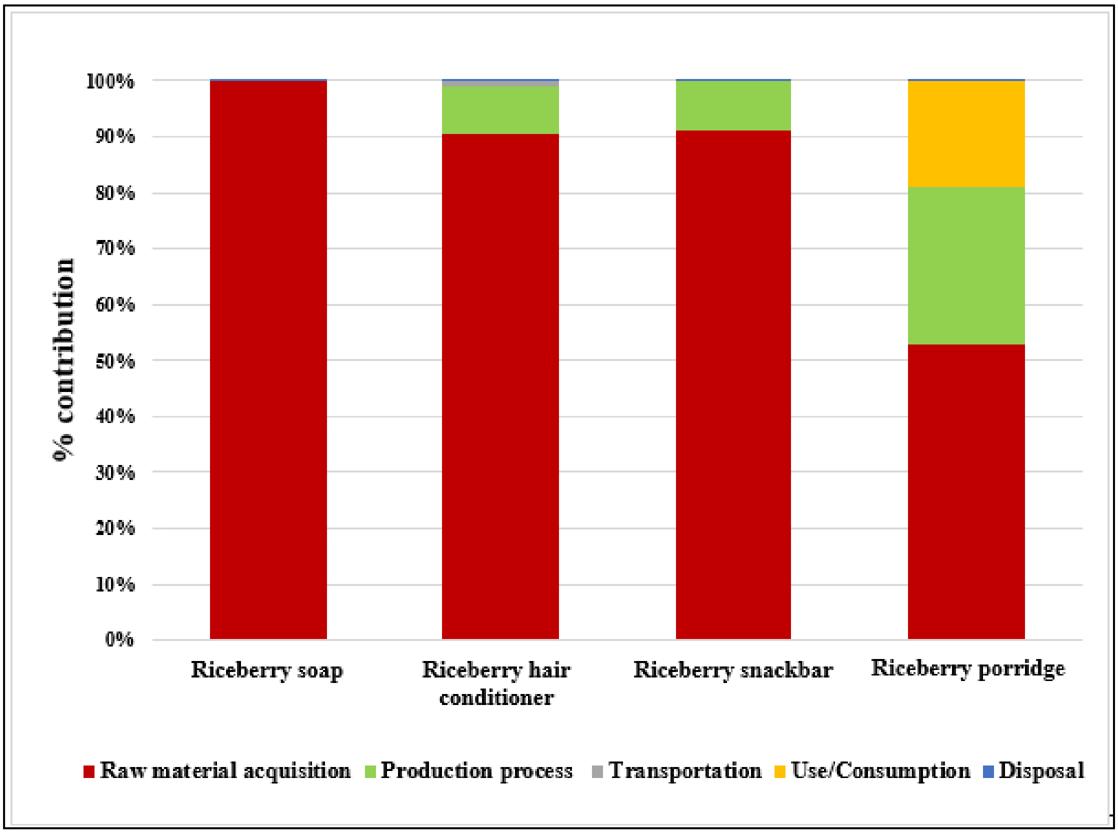

Figure 23 LCA contribution results on human health cancer effects indicator

Figure 24 showed the comparative LCIA results of products studied in the Acidification indicator. The LCIA result of riceberry products in the acidification indicator showed that all products studied had the key hotspot at the raw materials acquisition stage. For non-food products, riceberry soap had the impacts on the acidification indicator equal to 3.66E-03 mol H^{+}e with the impact's contribution causing from the raw materials acquisition stage (99%), and other stages less than 1%, while riceberry hair conditioner had the impact on acidification indicator equal to 3.04E-03 mol H^{+}e. with the impact contribution caused from the raw materials acquisition stage (86%), the production process (4%), transportation (9%) and other stages less than 1%. For food products, riceberry porridge had the impacts on the acidification indicator equal to 1.95E-03 mol H^{+}e. with the impacts contribution caused from raw materials acquisition stage (64%) followed by the production process (24%), and use stage (12%) and other stages less than 1%, while riceberry snack bar had the impact on the acidification indicator equal to 1.38E-03 mol H^+e. with the impact contribution causing from the raw materials acquisition stage (88%), followed by the production process (12%), and other stages less than 1%.

Comparing various riceberry products, it was found that riceberry soap had the highest impact on the Acidification indicator (3.66E-03 mol H^+e.). The key hotspot causing significant impact was associated with the raw materials acquisition stage (99%) from the production of coconut oil (75%) especially the crude coconut oil production, rice bran oil (14%) and NaOH (7%). The lowest impact on the Acidification indicator was riceberry snack bar (1.38E-03 mol H^+e) due mainly to lower composition of ingredients and low impacts of ingredients used for making riceberry snack bar. However, the key hotspot causing significant impacts was also Associated with the raw materials acquisition stage (88%) resulted from the production of peanut butter (28%), and riceberry farming (25%)

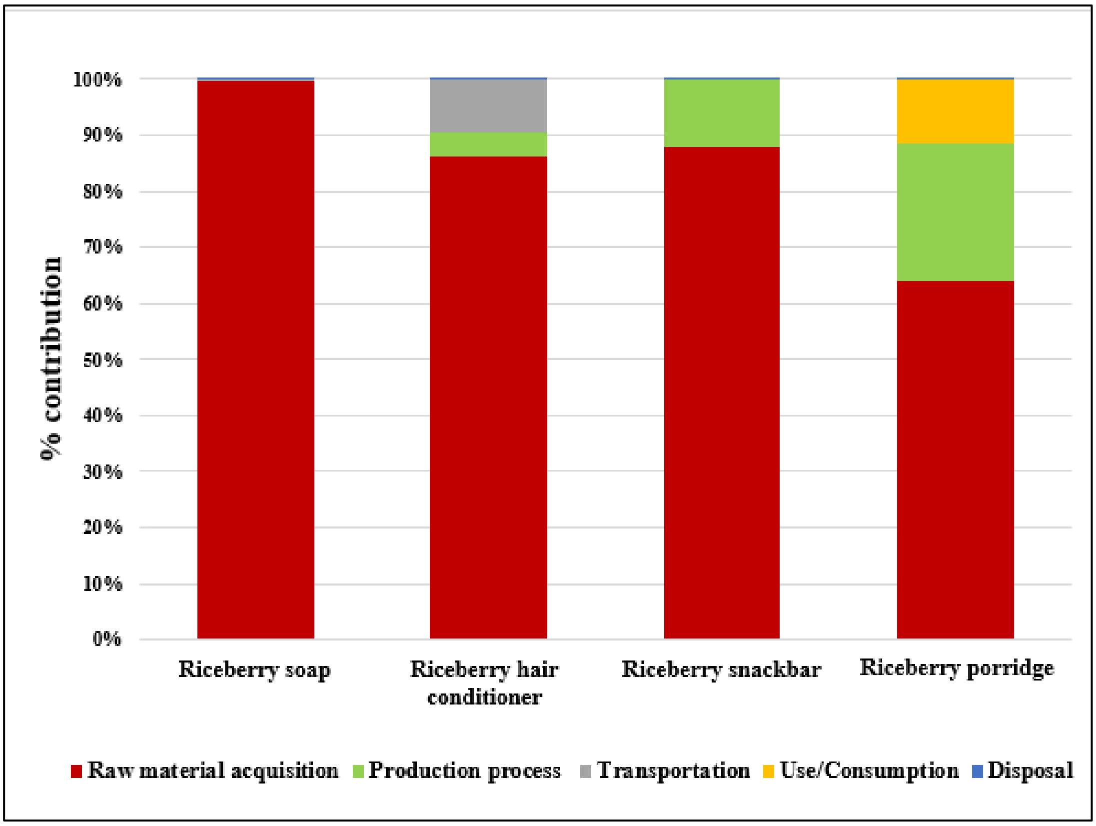

Figure 24 LCA contribution results on acidification indicator

Figure 25 showed the comparative LCIA results of products studied in Fresh water aquatic eco-toxicity indicator. The LCIA result of riceberry products in Fresh water aquatic eco-toxicity indicator showed that all products studied had the key hotspot at the raw materials acquisition stage. For non-food products, riceberry soap had the impact on the freshwater aquatic eco-toxicity indicator equal to 7.12E+00 CTUe with the impact contribution caused from the raw materials acquisition stage (99%), and other stages less than 1%, while riceberry hair conditioner had the impact on the freshwater aquatic eco-toxicity indicator equal to 6.23E-01 CTUe with the impact contribution caused from the raw materials acquisition stage (91%), production process (2%), transportation (6%) and other stages less than 1%. For food products, riceberry porridge had the impact on the freshwater aquatic eco-toxicity indicator equal to 1.12E+00 CTUe with the impact contribution caused from the raw materials acquisition stage (94%) followed by the production process (4%), and consumption stage (2%) and other stages less than 1%, while riceberry snack bar had the impact on freshwater aquatic eco-toxicity indicator equal to 2.58E+00 CTUe with the impacts contribution causing from the raw materials acquisition stage (99%), and other stages less than 1%.

Comparing various riceberry products, it was found that riceberry soap had the highest impact on the freshwater aquatic eco-toxicity indicator (7.12E+00 CTUe). The key hotspot causing significant impacts was associated with the raw materials acquisition stage from the production of rice bran oil (80%) especially the rice farming stage, coconut oil (19%). The lowest impact on the freshwater aquatic eco-toxicity indicator was riceberry hair conditioner (6.23 E-01 CTUe) due mainly to lower impacts of the chemical ingredients in this indicator such as starter Dehydax wax AB has impact only 2.82 E-01 CTUe.

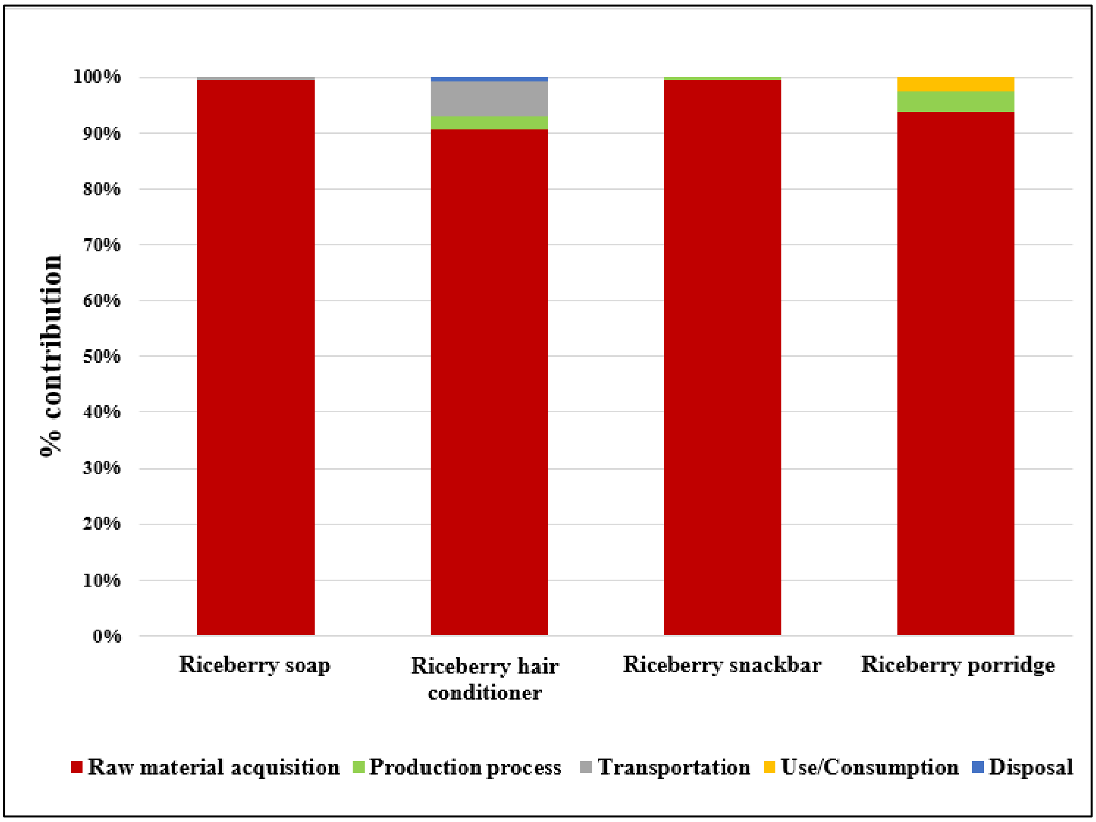

Figure 25 LCA contribution results on fresh water aquatic eco-toxicity ind*icator*

Figure 26 showed the comparative LCIA results of products studied in water scarcity indicator. The LCIA result of riceberry products in the water scarcity indicator showed that all products studied had the key hotspot at the raw materials acquisition stage. For non-food products, riceberry soap had the impact on the water scarcity indicator equal to 3.97E-01 m^3depriv. with the impact contribution caused from the raw materials acquisition stage (99%), and other stages less than 1%, while riceberry hair conditioner had the impacts on the water scarcity indicator equal to 5.85E-01 m^3depriv. with the impact contribution caused from the raw materials acquisition stage (99%), and other stages less than 1%. For food products, riceberry porridge had the impact on water scarcity indicator equal to 1.07E+00 m^3depriv.with the impact contribution caused from the raw materials acquisition stage (96%) follow by the production process (2%), and consumption stage (2%) and other stages less than 1%, while riceberry snack bar had the impacts on water scarcity indicator equal to 8.40E-01 m^3depriv. with the impact contribution caused from the raw materials acquisition stage (99%), and other stages less than 1%.

Comparing various riceberry products, it was found that riceberry porridge had the highest impact on the water scarcity indicator (1.07E+00 m^3depriv). The key hotspot that caused significant impacts was associated with the raw materials acquisition stage (96%) resulted from the production of riceberry rice especially on riceberry rice farming (95%) and shiitake mushroom production (6%), the lowest impact on the water scarcity indicator was riceberry soap due mainly to lower composition of ingredients and low impact of ingredients used for making riceberry soap. However, the key hotspot that caused a significant impact was also associated with the raw materials acquisition stage (99%) resulted from the production of rice bran oil especially in the farming stage (59%), but it caused impact on the water scarcity indicator only 2.35E-01 m^3depriv.

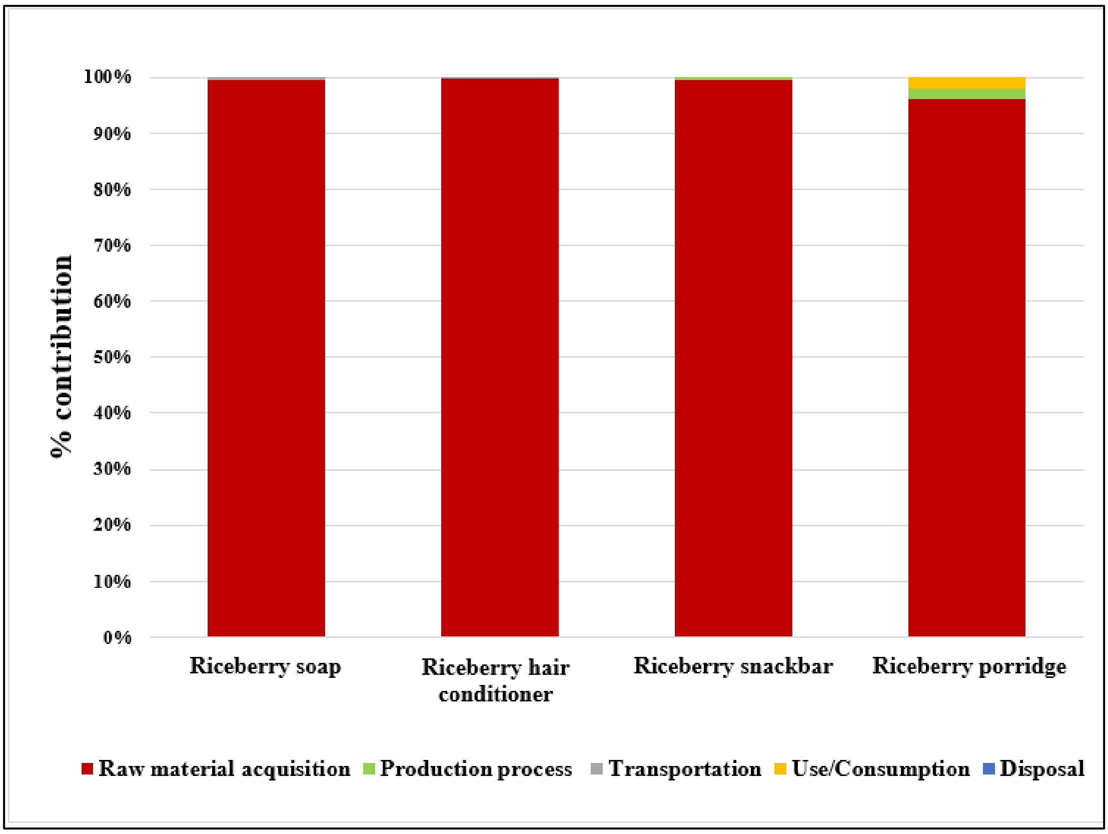

Figure 26 LCA contribution results on water scarcity indicator

Figure 27 showed the comparative LCIA results of products studied in the used energy indicator. The LCIA result of riceberry products in used energy indicator showed that all studied products had the key hotspot at the raw materials acquisition stage. For non-food products, riceberry soap had the impact on the used energy indicator equal to 3.21E+00 MJ with the impact contribution caused from the raw materials acquisition stage (99%), and other stage less than 1%, while riceberry hair conditioners had the impact on energy use indicator equal to 6.36E+00 MJ. with the impact contribution caused from the raw materials acquisition stage (70%), production process (20%), transportation (9%), and other stages less than 1%. For food products, riceberry porridge had the impacts on energy use indicator equal to 3.69E+00 MJ. with the impact contribution causing from the raw materials acquisition stage (40%) followed by the production process (37%), and the consumption stage

(22%) and other stages less than 1%, while riceberry snack bar had the impact on energy use indicator equal to 2.55E+00 MJ. with the impact contribution caused from the raw materials acquisition stage (82%), production process (17%) and other stages less than 1%.

Comparing various riceberry products, it was found that riceberry hair conditioner had the highest impact on the used energy indicator (6.36E+00 MJ). The key hotspot that caused significant impacts were associated with the raw materials acquisition stage (70%) resulted from the production of PET bottle (50%), dehydax wax AB (20%), and the preservative (10%), the lowest impact on energy use indicator was riceberry snack bar due mainly to low impacts of ingredients used for making riceberry snack bar. However, the key hotspot that caused significant impact was also associated with the raw materials acquisition stage (99%) resulting from the production of packaging bag OPP (34%), but its cause impact on energy used indicator only 7.09E-01 MJ.

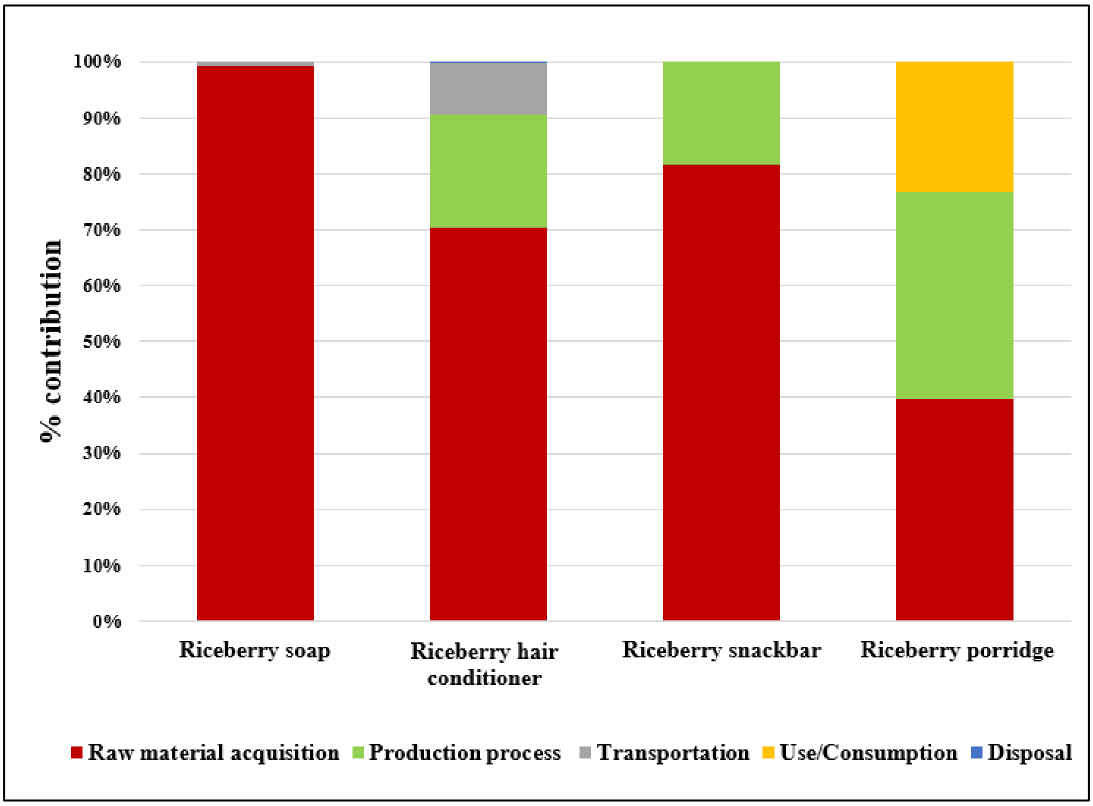

Figure 27 LCA contribution results on energy use indicator

2.2 LCIA result of raw materials contribution

The raw materials acquisition stage was the main stage of impact contribution for each riceberry product, the result of impact contribution as shown in **Figure 28 - 31.**

2.2.1 Riceberry soap

Figure 28 showed that coconut oil was the main contribution to the raw materials acquisition stage, especially on crude coconut oil production by caused a significant impact on the global warming indicator (75%), human health cancer effects indicator (91%), the acidification indicator (75%) and the used energy indicator (78%). While rice bran oil caused the high impact contribution on the freshwater aquatic eco-toxicity indicator (80%) and the water scarcity indicator (59%) resulting from the riceberry farming stage for riceberry rice used as a raw material in the rice bran oil production.

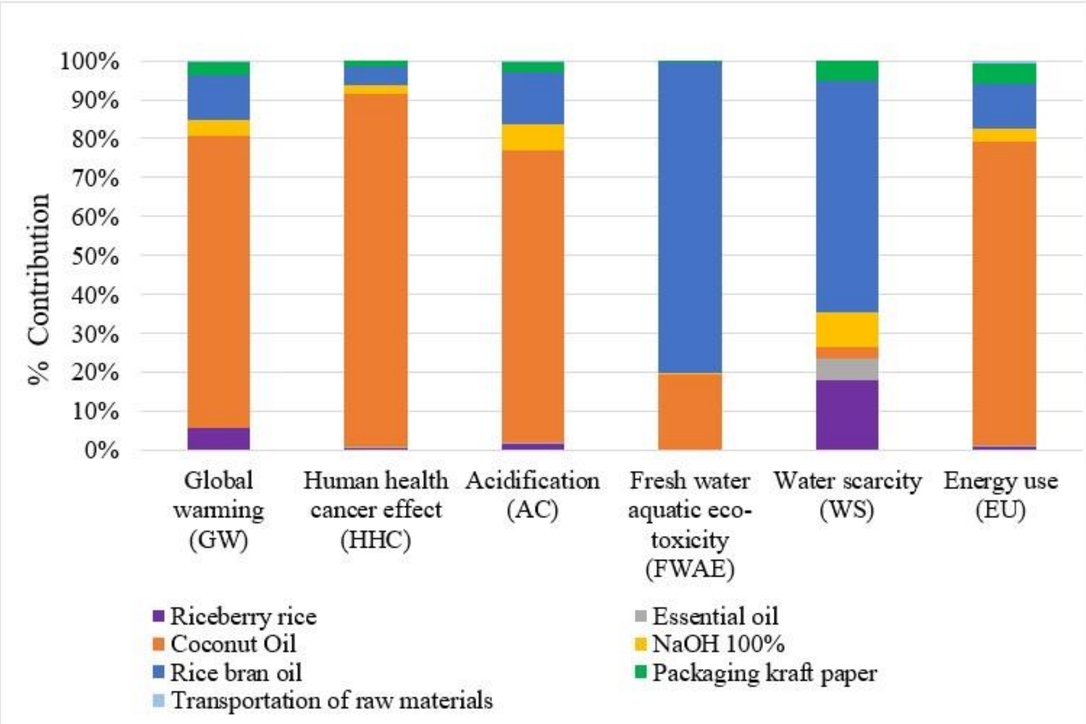

Figure 28 Contribution analysis of life cycle environmental impacts associated with the raw material acquisition for riceberry soap

2.2.2 Riceberry hair conditioner

Figure 29 showed that starter (Dehaydax wax AB) was the main contribution to the raw materials acquisition stage by caused a significant impact on the global warming indicator (46%), acidification indicator (46%), and the freshwater aquatic eco-toxicity indicator (50%), while riceberry rice caused the high impact contribution on the water scarcity indicators for 85% resulting from the water consumption during riceberry farming stage. Moreover, the production of PET bottles for packaging caused significant impacts on the energy used indicators by 50% resulting from the energy consumption on the production process of virgin PET plastic for PET bottle production.

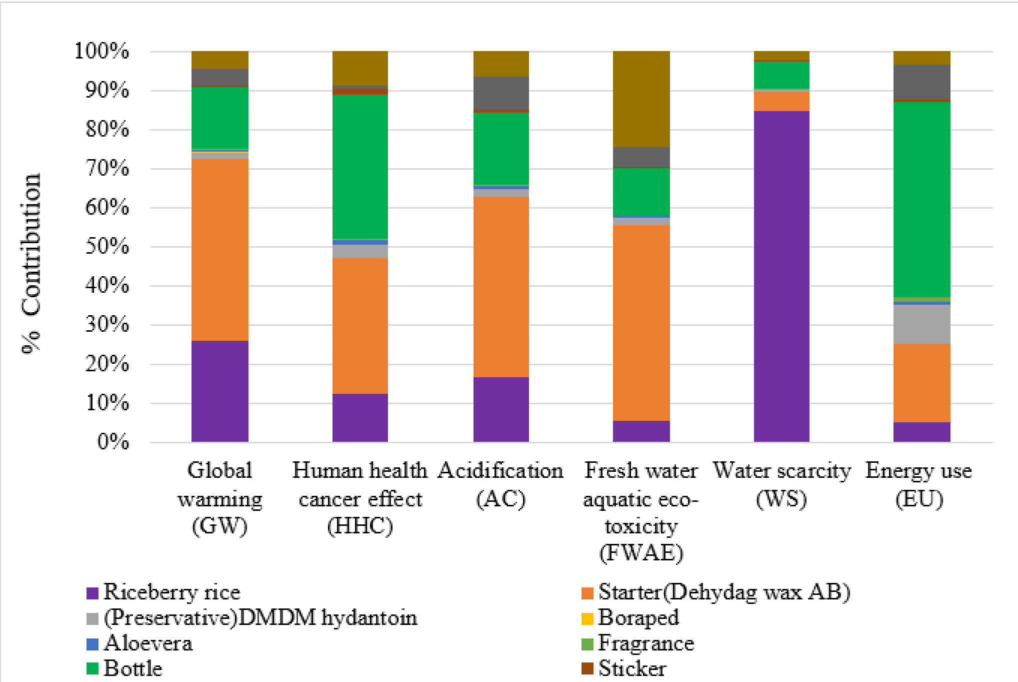

Figure 29 Contribution analysis of life cycle environmental impacts associated with the raw material acquisition for riceberry hair conditioner

2.2.3 Riceberry snack bar

Figure 30 showed that riceberry rice, rice bran oil, and peanut butter were the main contribution to the raw materials acquisition stage. Riceberry rice caused a significant impact on the global warming indicator (50%), water scarcity indicator (42%) and acidification indicator (25%), while rice bran oil caused the significant impact on the freshwater aquatic eco-toxicity indicator (59%), and peanut butter caused the significant impact on human health cancer effects indicator (41%). Moreover, packaging production caused a significant impact on the used energy indicator by (34%).

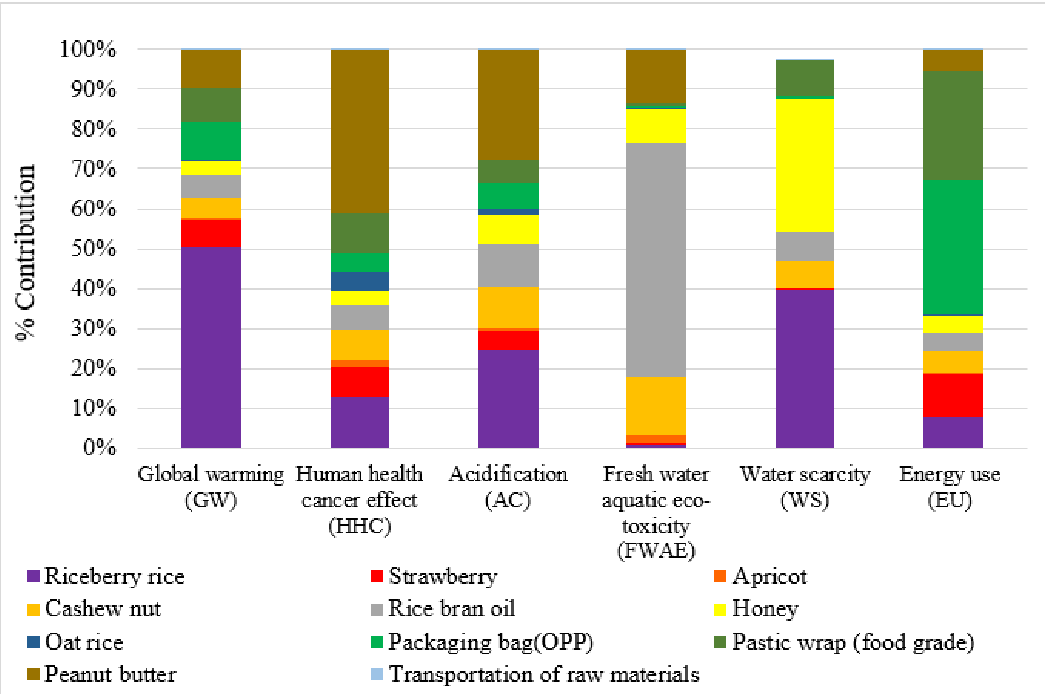

Figure 30 Contribution analysis of life cycle environmental impacts associated with the raw material acquisition for riceberry snack bar

2.2.4 Riceberry porridge

Figure 31 showed that broken riceberry rice was the main contribution to the raw materials acquisition stage by caused significant impacts on the global warming indicator (85%), human health cancer effects indicator (56%), acidification indicator (66%) and water scarcity indicator (95%) resulting from emission generated during riceberry farming stage. While shiitake mushroom caused a significant impact on the freshwater aquatic eco-toxicity indicator by 78% caused from the production process. Moreover, the packaging production of this product also caused the highest impact on the used energy indicator (53%).

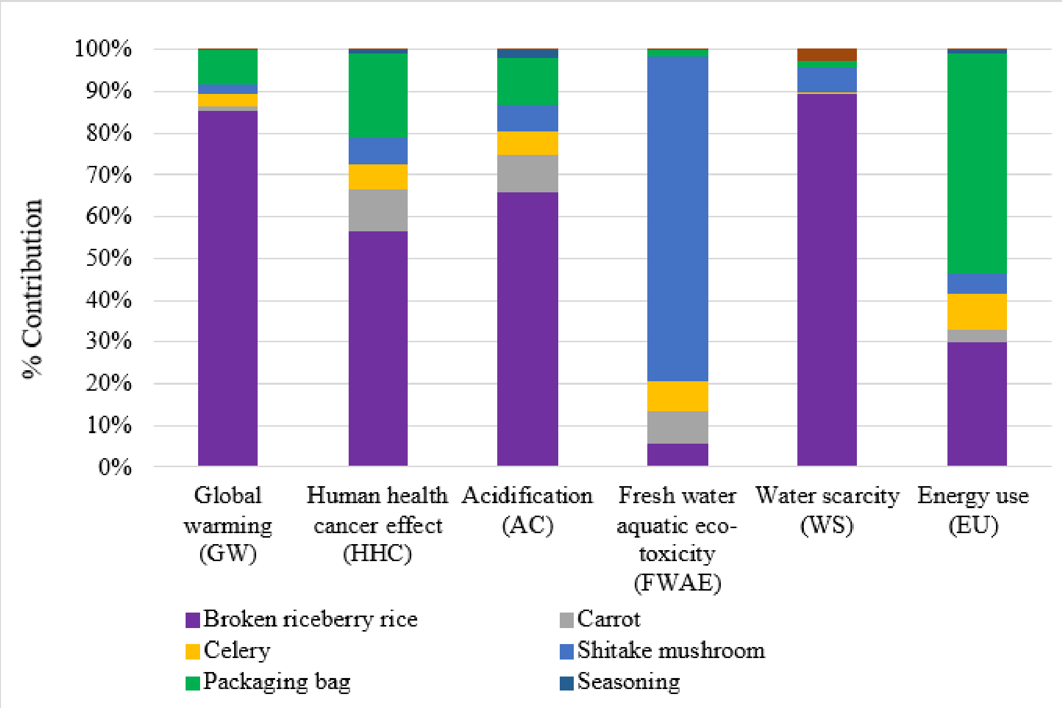

Figure 31 Contribution analysis of life cycle environmental impacts associated with the raw material acquisition for riceberry porridge

3. **Eco-efficiency assessment results**

This study was not limited only to LCA for environmental performance evaluation but also considered the economic performance of riceberry products. Based on this study the following data are the eco-efficiency assessment results of each riceberry product.

3.1 Products system value assessment

The product's system value in this study considers the selling price of each product in the market. However, it should be noted that the price of products varied based on the market positioning of different products. The willingness to pay from the consumer was based on the quality of products as well as the features and aesthetics of packaging materials that reflect the quality of products inside. Packaging should fulfill all its functions for consumers willing to pay a high price (Atagan *et al.*, 2013). Nevertheless, the selling price can still serve as a proxy of the product value, especially from the perspective of the producer. The selling prices of each product are shown in **Table 30.**

Table 35 Products system value of riceberry products

	Products	Sold unit	Selling price	
1	Riceberry soap	90 g	90 THB	2.8 USD
2	Riceberry hair conditioner	250 ml	150 THB	4.5 USD
3	Riceberry porridge	35 g	20 THB	0.6 USD
4	Riceberry snack bar	50 g	35 THB	1.1 USD

1 USD = 32.39: Foreign Exchange Rates as of 10 December 2019

3.2 Eco-efficiency assessment results

The eco-efficiency result of riceberry products revealed that the riceberry soap has the highest eco-efficiency values in the global warming indicator, equal to 6.45E+00 USD/kgCO_2e. This was mainly associated with a high selling price setting from the market positioning of the product in the health and wellness niche markets both in Thailand and overseas. The calculation of production cost based on craftsman and selling price resulted in almost 90% of gross profit. Health-conscious consumers were proved to have the ability to buy good quality products at a high and reasonable (Kongdechakul, 2018) While the lowest eco-efficiency value in the global warming indicator was riceberry porridge which equal to 1.02E+00 USD/kgCO_2e due to the lowest selling price when compared to other products. The results of the eco-efficiency value in the global warming indicator for each product was shown in **Table 31.**

For the human health cancer effects indicator, it was revealed that the riceberry hair conditioner has the highest eco-efficiency values equal to 9.26E+08 USD/CTUh. This is also mainly associated with a high selling price setting from the market positioning and lower impact on the environment on this indicator. While the lowest eco-efficiency value in human health cancer effects indicator was riceberry porridge which equals to 1.73E+08 USD/CTUh. due to the lowest selling price when compared to other products. The results of the eco-efficiency value in the human health cancer effects indicator for each product was shown in **Table31.**

For the acidification indicator, it was revealed that the riceberry snack bar has the highest eco-efficiency value equal to 7.95E+02 USD/ mol H^+e. This was mainly associated with the lowest impact on the environment when compared to other products. While the lowest eco-efficiency value in acidification indicator was also riceberry porridge and also caused the lowest selling price when compared to other products. The results of the eco-efficiency value in the acidification indicator for each product was shown in **Table31.**

For the freshwater aquatic eco-toxicity indicator, it was revealed that riceberry hair conditioner has the highest eco-efficiency values equal to 7.23E+00 USD/CTUe. This is also mainly associated with a high selling price setting from the market positioning and lowest impact on the environment when compared to other products. While the lowest eco-efficiency value in freshwater aquatic eco-toxicity indicator was riceberry soap which equals to 3.93E-01 USD/CTUe. Causing from the highest impacts on the environment in freshwater aquatic eco-toxicity indicator when compared to other products. The results of eco-efficiency value in the freshwater aquatic eco-toxicity indicator for each product was shown in **Table31.**

For the water scarcity indicator, it was revealed that riceberry hair conditioner has the highest eco-efficiency values equal to 7.70E+00 USD/ m^3depriv. This is also mainly associated with a high selling price setting from the market positioning. While the lowest eco-efficiency value in the water scarcity indicator is also riceberry porridge which equals to5.62E-01USD/m^3depriv and also caused the lowest selling price when compared to other products. The results of the eco-efficiency value in the water scarcity indicator for each product was shown in **Table31.**

For the used energy indicator, it was revealed that riceberry soap has the highest eco-efficiency values equal to 8.72E-01 USD/MJ. This mainly associated with the high selling price of this product and lower impact on the environment when compared to riceberry hair conditioner and other products. While the lowest eco-efficiency value in energy use indicator was riceberry porridge which equals to 1.63E-01 USD/MJ and it also has the lowest selling price when compared to other products. The result of the eco-efficiency value in the used energy indicator for each product was shown in **Table31.**

Table 36 Eco-efficiency value of original riceberry products

Impact category	Riceberry soap	Riceberry hair conditioner	Riceberry porridge	Riceberry snack bar
Global warming (USD/kgCO_2e)	6.45E+00	5.54E+00	1.02E+00	4.02E+00
Human health cancer effects (USD/CTUh)	2.11E+08	9.26E+08	1.73E+08	3.46E+08
Acidification (USD/mol H^+e)	7.65E+02	1.48E+03	3.07E+02	7.95E+02
Fresh water aquatic eco-toxicity (USD/CTUe)	3.93E-01	7.23E+00	5.36E-01	4.26E-01
Water scarcity (USD/m^3depriv)	7.05E+00	7.70E+00	5.62E-01	1.31E+00
Energy use (USD/MJ)	8.72E-01	7.07E-01	1.63E-01	4.32E-01

DISCUSSION

The LCA and eco-efficiency assessment results were integrated to provide insights on recommendations at the national policy level on which processed riceberry products should be promoted, and to make decisions at the company level for product development aiming to increase the eco-efficiency value. The improvement of product's eco-efficiency value consists of two ways. The environmental performance improvement can be made by considering the key hotspot highlights in LCIA results for impacts reduction opportunities. For example, using a life cycle assessment at the beginning of product design (eco-design) and selecting environmentally friendly ingredients could help with environmental impact reduction. For economic performance improvement, the increase of selling prices could be the other way to increase the eco-efficiency value in addition to the decreasing of environmental performance. Putting the products at a different marketplace could be a potential way to put up a higher price. For instance, riceberry hair conditioners sell in luxury department stores can increase more selling price. While riceberry soap could be sold at the beauty and healthy shops where consumers have more willingness to buy organic or natural-based products.

Pricing strategies could be a marketing of premium products by increasing more value to the products, offering a new customer experience, or promotion by lowering the price if the customer buys a riceberry snack along with a coffee. Moreover, eco-label that signals the green and sustainability of products can increase the price and popularity for niche consumer groups. However, this study was focused on the decreasing life cycle environmental impact, and it was assumed that the selling prices of the riceberry products remained the same. The results of the life cycle assessment indicated that the raw material acquisition stage was the major hotspot contributing more than 50% to all impacts for all the products followed by the production process of each riceberry product. Based on these findings, improvement opportunities explored in the study focused on the riceberry farming stage by applying alternate wetting and drying water practice (AWD) the farming techniques, modification of recipe, and the re-designing of packaging. In addition, it is particularly important that the selected alternative ingredients must have similar nutrients, flavor, or texture to ensure that the taste and quality would be maintained.

1. Integration of LCA results for products development

Tables 32-35 show the life cycle impact assessment indicators before and after the environmental performance improvement of riceberry soap, riceberry porridge, and riceberry snack bar. The practicality of proposed improvement opportunities was identified through consultation with manufacturing companies.

1.1 Riceberry soap

As identified earlier that using coconut oil was a key hotspot, therefore, it was proposed to replace with another oil with similar properties, it was suggested that palm kernel oil could be used because both 2 oils were classified as lauric oils due to their high levels of lauric acid (Bhattacharya, 2019). In addition, palm kernel oil also contains similar properties such as bubbly, hardness, cleansing condition, and a lower saponification value. Moreover, the new recipe could also use less NaOH. On top of that, the production cost could also be reduced as the price of palm kernel oil was rather lower. Apart from that, riceberry rice could be sourced from the rice field by applying the Alternate Wetting and Drying (AWD) method that had the potential to reduce GHG emissions. It was found that using palm kernel oil could potentially reduce the impact on the human health cancer effects by 43% and other environmental impacts could be reduced from 1% to 36%. It was also revealed that riceberry rice obtained from the AWD rice farming site could potentially reduce the impact on the global warming by 20% as shown in **Table 32**.

Table 37 LCIA and improvement result of riceberry soap.

	LCIA results		
	Before improvement	**After improvement**	**% Reduction**
Global warming ($kgCO_2e$)	4.34E-01	3.49E-01	20
Human health cancer effects (CTUh)	1.33E-08	7.60E-09	43
Acidification (mol H^+e)	3.66E-03	2.63E-03	28
Fresh water aquatic eco-toxicity (CTUe)	7.12E+00	6.52E+00	9
Water scarcity (m^3depriv)	3.97E-01	3.95E-01	1
Energy use (MJ)	3.21E+00	2.06E+00	36

1.2 Riceberry hair conditioner

For riceberry hair conditioner, the options for decreasing the life cycle environmental impacts were rather limited due mainly to great concern over the effects of changing the formula to the product's function. Only one ingredient could be changed, which was the shifting to riceberry from the AWD method. Another option for the environmental performance improvement was focused on the re-designing for eco-packaging by using recycled PET bottles. These improvements could potentially reduce all environmental impact indicators by 7-51% resulting from the lower energy consumption of recycled PET bottles and reduction of methane gas emission during the farming stage as shown in **Table 33.**

Table 38 LCIA and improvement result of riceberry hair conditioner.

	LCIA results		
	Before improvement	**After improvement**	**% Reduction**
Global warming ($kgCO_2e$)	8.13E-01	5.97E-01	27
Human health cancer effects (CTUh)	4.86E-09	3.53E-09	27
Acidification (mol H^+e)	3.04E-03	2.48E-03	18
Fresh water aquatic eco-toxici (CTUe)	6.23E-01	5.78E-01	7
Water scarcity (m^3depriv)	5.85E-01	5.16E-01	12
Energy use (MJ)	6.36E+00	3.10E+00	51

1.3 Riceberry porridge

For riceberry porridge, the riceberry rice from the AWD method could be used for replacement. The manufacturing company also proposed to have a new recipe especially for consumers who do not like the smell of celery and vegetables, by removing the celery and adding more mushrooms instead. In addition, the redesigning of packaging from a laminated plastic bag (polypropylene and polyethylene terephthalate laminated with aluminum foil) to a paper cup offered as a ready-to-eat product to tackle a modern lifestyle was also considered. The new design of packaging could potentially reduce the impact on global warming by 34% and the used energy indicator by 20%. This would also reduce the other environmental impacts ranging from 1% to 15% as shown in **Table 34.**

Table 39 LCIA and improvement result of riceberry porridge.

	LCIA results		
	Before improvement	**After improvement**	**% Reduction**
Global warming ($kgCO_2e$)	5.90E-01	3.90E-01	34
Human health cancer effects (CTUh)	3.46E-09	2.95E-09	15
Acidification (mol H^+e)	1.95E-03	1.75E-03	10
Fresh water aquatic eco-toxicity (CTUe)	1.12E+00	1.02E+00	9
Water scarcity (m^3depriv)	1.07E+00	1.06E+00	1
Energy use (MJ)	3.69E+00	2.94E+00	20

1.4 Riceberry snack bar

For the riceberry snack bar, changing to the riceberry from the AWD method could be applied. Through consultation with the manufacturing company, the recipe could be modified by using different fruits that offer similar flavors. Peanut could be used as an alternative ingredient to replace cashew nut, and pineapple could be used as an alternative ingredient to replace apricot. It is particularly important that the selected alternative ingredients still have similar nutrients, flavor, or texture to ensure that the taste would be satisfied and using of pineapple was encouraged to enhance the strength of using local fruit as shown in **Table 35.** By implementing all options, it was found that the impact on global warming could potentially be reduced by 32% and the impact on energy use indicators could potentially be reduced by 27%. In addition, the modification of the recipe had the potential to reduce the production cost due to cheaper raw materials used.

Table 40 LCIA and improvement result of riceberry snack bar.

	LCIA results		
	Before improvement	**After improvement**	**% Reduction**
Global warming ($kgCO_2e$)	2.74E-01	1.86E-01	32
Human health cancer effects (CTUh)	3.18E-09	2.97E-09	7
Acidification (mol H^+e)	1.38E-03	1.27E-03	8
Fresh water aquatic eco-toxicity (CTUe)	2.58E+00	2.16E+00	16
Water scarcity (m^3depriv)	8.40E-01	6.87E-01	18
Energy use (MJ)	2.55E+00	1.86E+00	27

2. Integration of Eco-efficiency assessment results for products development

In this section, the results of eco-efficiency assessment between before and after improvement of riceberry products were compared in **Table 36-39**. The percentage of eco-efficiency increase were caused by the integration of LCA results for products development.

2.1 Riceberry soap

Table 36 reported the eco-efficiency of riceberry soap in 6 impacts indicators because the selling price was identical in both before and after improvement products (2.8 USD/Unit) as shown in **Table 30**. The eco-efficiency increase resulted from changing to the riceberry rice from the AWD method, replacing coconut oil with similar properties ingredients such as palm kernel oil. The decreasing environmental impacts resulted in higher eco-efficiency values ranging from 1-75%: 75 % for human health cancer affects and 56% for energy use.

Table 41 Eco-efficiency assessment and improvement result of riceberry soap.

Eco-efficiency			
	Before improvement	**After improvement**	**% Eco-efficiency increasing**
Selling Price	2.8	2.8	
Global warming (USD/kgCO_2e)	6.45E+00	8.02E+00	24
Human health cancer effects (USD/CTUh)	2.11E+08	3.69E+08	75
Acidification (USD/mol H^+e)	7.65E+02	1.06E+03	39
Fresh water aquatic eco-toxicity (USD/CTUe)	3.93E-01	4.30E-01	9
Water scarcity (USD/m^3depriv)	7.05E+00	7.09E+00	1
Energy use (USD/MJ)	8.72E-01	1.36E+00	56

2.2 Riceberry hair conditioner

Table 37 reported the eco-efficiency of riceberry hair conditioner in 6 impacts indicators because the selling price was identical in both before and after improvement products (4.5 USD/Unit) as shown in **Table 30**. The eco-efficiency increasing resulted from re-design for eco-packaging by using recycled PET bottles and shifting from traditional farming practice to alternative wetting and drying water practice (AWD) during the farming stage. The decreasing environmental impacts resulted in higher eco-efficiency values ranging from 8-105%: 105% for energy and followed by 38% for human health cancer effects. The eco-efficiency increasing resulted from

Table 42 Eco-efficiency assessment and improvement result of riceberry hair conditioner.

Eco-efficiency			
	Before improvement	**After improvement**	**% Eco-efficiency increasing**
Selling Price	4.5	4.5	
Global warming (USD/kgCO_2e)	5.54E+00	7.54E+00	36
Human health cancer effects (USD/CTUh)	9.26E+08	1.28E+09	38
Acidification (USD/mol H^+e)	1.48E+03	1.82E+03	23
Fresh water aquatic eco-toxicity (USD/CTUe)	7.23E+00	7.78E+00	8
Water scarcity (USD/m^3depriv)	7.70E+00	8.72E+00	13
Energy use (USD/MJ)	7.07E-01	1.45E+00	105

2.3 Riceberry porridge

Table 38 reported the eco-efficiency of riceberry porridge in 6 impacts indicators because the selling price was identical in both original and after improvement products (0.6 USD/Unit) as shown in **Table 30.** The eco-efficiency increasing resulted from changing to the riceberry from the AWD method, using alternative ingredients with a similar level of nutrients (such as shiitake mushroom), and replacing the celery to add a flavor especially for several people who do not like the smell of celery. The decreasing environmental impacts resulted in higher eco-efficiency values ranging from 1-51%: 51% for global warming 26% for the used energy. On top of that, the re-designing of packaging by changing the normal a Laminated plastic bag (polypropylene and polyethylene terephthalate laminated with aluminum foil) into a paper cup.

Table 43 Eco-efficiency assessment and improvement result of riceberry porridge.

Eco-efficiency			
	Before improvement	**After improvement**	**% Eco-efficiency increasing**
Selling Price	0.6	0.6	
Global warming (USD/kgCO_2e)	1.02E+00	1.54E+00	51
Human health cancer effects (USD/CTUh)	1.73E+08	2.03E+08	17
Acidification (USD/mol H^+e)	3.07E+02	3.42E+02	12
Fresh water aquatic eco-toxicity (USD/CTUe)	5.36E-01	5.87E-01	10
Water scarcity (USD/m^3depriv)	5.62E-01	5.67E-01	1
Energy use (USD/MJ)	1.63E-01	2.04E-01	26

2.4 Riceberry snack bar

Table 39 reported the eco-efficiency of riceberry snack bar in 6 impacts indicators because the selling price was identical in both before and after improvement products (1.1 USD/Unit) as shown in **Table 30**. The eco-efficiency increasing resulted from replacing cashew nut and apricot with pineapple due to the similar nutrients, texture and flavor, including shifting from traditional farming practice to alternative wetting and drying water practice (AWD) during the farming stage. The decreasing environmental impacts resulted in higher eco-efficiency values ranging from 7-48%: 48% for global warming and 37% for energy use.

Table 44 Eco-efficiency assessment and improvement result of riceberry snack bar

Eco-efficiency			
	Before improvement	**After improvement**	**% Eco-efficiency increasing**
Selling Price	1.1	1.1	
Global warming (USD/kgCO_2e)	4.02E+00	5.93E+00	48
Human health cancer effects (USD/CTUh)	3.46E+08	3.71E+08	7
Acidification (USD/mol H^+e)	7.95E+02	8.67E+02	9
Fresh water aquatic eco-toxicity (USD/CTUe)	4.26E-01	5.09E-01	20
Water scarcity (USD/m^3depriv)	1.31E+00	1.60E+00	22
Energy use (USD/MJ)	4.32E-01	5.90E-01	37

3. Comparative results of eco-efficiency between white rice and riceberry rice

To visualize it, which would be very interesting to compare the eco-efficiency values between Hom Mali rice (white rice) and riceberry rice. **Table** 40 showed the detail of studied white rice and riceberry rice products and **Figure 32** reports the eco-efficiency as per global warming of various products from white rice and riceberry. Based on the products in our study, riceberry products were substantially outperforming in terms of selling price 1 kg of riceberry rice can generate more value-added when processing into riceberry products and it is also causing lower impacts on the environment when compared between each product in terms of the sold unit. The overall comparative results indicated that riceberry milled rice products had higher eco-efficiency values compared to the white milled rice products. The eco-efficiency values of riceberry processed products especially for non-food products were even much higher than the white milled rice product. Although the impact on global warming associated with riceberry milled rice was higher, this implies that the higher selling prices of riceberry milled rice, as well as riceberry processed products was a key factor leading to the higher eco-efficiency values. Therefore, processing riceberry products into high value-added products should be promoted for further development.

Table 45 Details of studied white rice and riceberry rice products

Products	Functional unit	LCIA result	Selling price
1. Hom Mali rice	1 kg	4.4 $kgCO_2e$ with the average yield 370 kg/rai (Mungkung et al., 2012)	40 baht or 1.2 USD per kg
2. Riceberry rice	1 kg	5.39 $kgCO_2e$ for average yield 427 kg/rai (Product Category Rules Rice Products (PCR) (TGO, 2017)).	109 baht or 3.3 USD/kg
3. Riceberry soap	90 g	4.34E-01 $kgCO_2e$	90 baht or 2.8 USD
4. Riceberry hair conditioner	250 ml	8.13E-01 $kgCO_2e$	150 baht or 4.5 USD
5. Riceberry porridge	35 g	5.90E-01 $kgCO_2e$	20 baht or 0.6 USD
6. Riceberry snack bar	50 g	2.74E-01 $kgCO_2e$	35 baht or 1.1 USD

USD = 32.39: Foreign Exchange Rates as of 10 December 2019

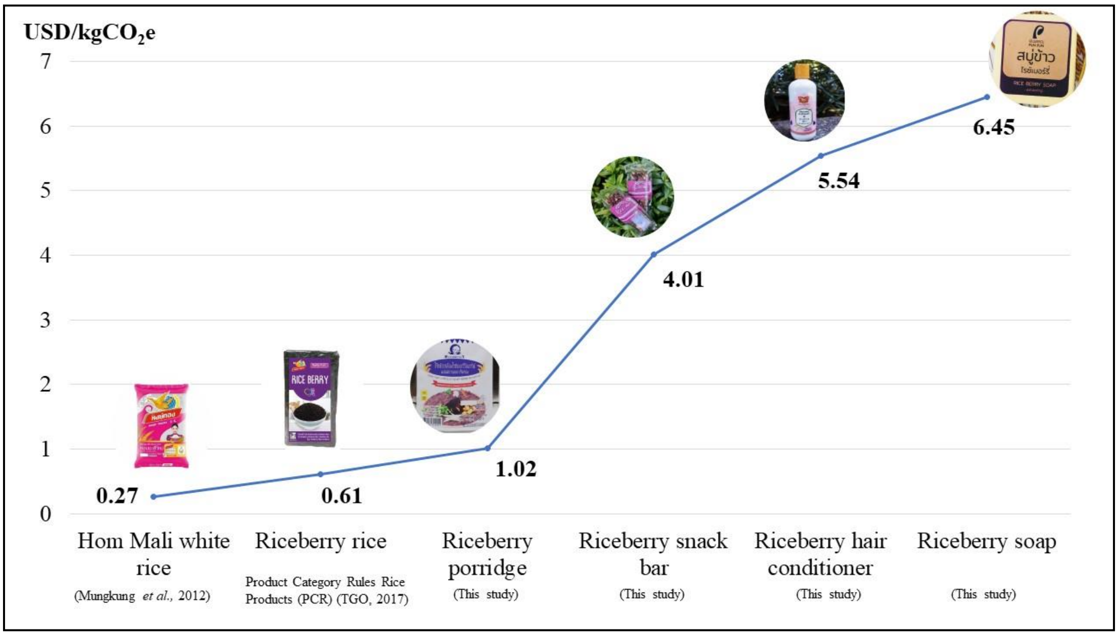

Figure 32 Comparative eco-efficiency values between white rice and Riceberry rice products

CONCLUSION AND RECOMMENDATIONS

CONCLUSION

Riceberry rice has been encouraged for producing high value-added products targeting for health and wellness niche markets via the national policy on Thailand 4.0. This study has demonstrated the application of Life Cycle Assessment (LCA) to evaluate the environmental performances of various riceberry products. Selected riceberry products covering both food and non-food products were included: riceberry soap, riceberry hair conditioner, riceberry snack bar, and riceberry porridge. The LCA results were used to identify the possible improvement options for better environmental performances. The integration of the environmental and economic performances of riceberry processed products were expressed in terms of eco-efficiency values, to provide the decision supporting information, to improve environmental and economic performances for private companies and to suggest which products should be further developed and promoted to move towards sustainability for policymakers.

For the LCA study, the system boundary was set from cradle to grave. The unit of analysis was defined as the sold unit of studied products: which were 90 g of riceberry soap, 250 ml of riceberry hair conditioner, 35 g of riceberry porridge, and 50 g of riceberry snack bar. The foreground data were collected from the primary data based on the annual production of manufacturers in 2019 and the associated background data were sourced from the life cycle inventory national databases and supplemented by international databases when necessary. The LCA results indicated that the raw material acquisition stage was the major hotspot for all studied products and significantly contributed more than 50% of all impacts for all studied products. It was found that the use of coconut oil and rice bran oil was the key issues for riceberry soap whereas dehydag wax AB and PET bottles were the main hotspots for riceberry hair conditioners. The main contributors were associated with broken riceberry rice and packaging materials for riceberry porridge, while peanut butter, riceberry rice, and packaging bag production was the main contributor to all impact indicators for riceberry snack. In addition to the raw material production, the used energy in the production process resulted in the impacts on energy use indicator for more than 20%. The calculation of eco-efficiency based on global warming and energy use indicators showed that riceberry soap being highest in eco-efficiency value, while others impact indicators showed that riceberry hair conditioner being highest, the high eco-efficiency of these two products resulted from high selling price setting from the market positioning. Among the four products studied, it turned out that the eco-efficiency value of riceberry porridge was lowest due to the lowest of selling price when compared with other products.

To increase the eco-efficiency values, there were two ways: decreasing the life cycle environmental impacts or increasing the selling prices of products. This study was focused on the environmental improvement opportunities by modifying the recipes and changing to the riceberry rice with the AWD method. The eco-profiles of riceberry soap could be improved by replacing coconut oil with palm kernel oil, which could potentially reduce all environmental impact indicators by 1-43%. All of these improvements had the potential to increase eco-efficiency by 1-75%. For riceberry hair conditioner recycled polyethylene terephthalate bottles for packaging and shifting from traditional farming practice to alternative wet and dry water practice during the farming stage could potentially increase the eco-efficiency by 8-105%, especially on the energy use indicator by 105% and the global warming indicator by 36%. For riceberry porridge, the improvement was focused on replacing celery with shiitake mushroom and re-designing the packaging by using paper cups which had the potential to increase the eco-efficiency value by 1-51%. For the riceberry snack bar, the improvement was focused on using peanuts and pineapple to replace the apricot and cashew nuts had the potential to increase the eco-efficiency value 7-48%. In summary, riceberry soap, riceberry hair conditioners, and riceberry snack bar should be promoted for further development towards the value-based economic system according to Thailand 4.0 because of their higher values.

RECOMMENDATIONS

The results from this study could be useful for private companies in the development of sustainable products. The eco-efficiency improvement could be achieved by changing the recipe to locally grown agricultural ingredients along with re-designing the packaging to be more environmentally friendly. Life cycle design should be considered from the very beginning of concept design for new products, aiming to optimize the environmental and economic performances. In addition, the LCA and eco-efficiency study could be used as supporting information for policy makers to move towards sustainability. This could be linked with the development of supportive policy and strategies to reforming the Thai riceberry rice industry. Furthermore, proposed strategies for reforming the Thai riceberry rice industry towards Thailand 4.0 could be enhanced via the following actions: (1) uplifting the riceberry rice farming practices to be more sustainable according to the international framework such as SRP (Sustainable Rice Platform) by considering environmental, social, and economic aspects, (2) improving the sustainability performance of the whole riceberry rice supply chain to be more sustainable according to the international framework such as SAFA (Sustainability Assessment of Food and Agriculture) by considering environmental, social, economic, and governance dimensions. These will support and contribute to the Thailand 4.0 policy aiming at security, prosperity, and sustainability especially in the field of sustainable agriculture. For future research, it was recommended to consider the increasing eco-efficiency values by integrating the effects of decreasing environmental impacts as well as increasing the value-added of the products. Marketing research on how to increase the value-added of the would be very useful. These will help in understanding the consumers' preferences and their perspectives on the riceberry products' values. Moreover, a variety of riceberry rice products should be studied especially cosmetic or pharmaceutical products as they have very high value- added.

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APPENDIX

Collection Date: …………………….

<table>
<tr><td>Name</td><td colspan="4">(Mr./Mrs/Ms.)</td></tr>
<tr><td rowspan="4">Address</td><td colspan="4">Name</td></tr>
<tr><td colspan="4">No.</td></tr>
<tr><td colspan="4">District</td></tr>
<tr><td colspan="4">Post No</td></tr>
<tr><td rowspan="2">Size of factory</td><td colspan="4">Area………..(Sq.m)</td></tr>
<tr><td colspan="4">No. of Employee</td></tr>
<tr><td rowspan="2">Business Type</td><td></td><td>Owner</td><td></td><td>Company</td></tr>
<tr><td></td><td>SME</td><td></td><td>Others</td></tr>
<tr><td>Production capacity</td><td></td><td></td><td></td><td></td></tr>
<tr><td>More detail</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5"></td></tr>
</table>

Flow chart for production process

Input	Quantity	Unit
Materials		
Resource and Production aids		

Output	Quantity	Unit
Products		
Waste		

Input	Quantity	Unit
Materials		
Resource and Production aids		

Output	Quantity	Unit
Products		
Waste		

Input	Quantity	Unit
Materials		
Resource and Production aids		

Output	Quantity	Unit
Products		
Waste		

Input	Quantity	Unit
Materials		
Resource and Production aids		

Output	Quantity	Unit
Products		
Waste		

Input	Quantity	Unit
Materials		
Resource and Production aids		

Output	Quantity	Unit
Products		
Waste		

Input	Quantity	Unit
Materials		
Resource and Production aids		

Output	Quantity	Unit
Products		
Waste		

Transportation of raw materials and products distribution

Lists	Unit	Quantity	Origin-Destination	Distance (km)	Type of Vehicle	Type of Fuel	Quantity of Fuel use	Loading capacity	Return capacity	Note
Raw materials										
Products Distribution										

Waste disposal

Lists	Waste disposal scenarios			
	Incineration	Land fill	Recycle	Others

Equipments and machines for production process

No.	Lists	Production process	Usage time (hr)	Electricity consumption (kWh)	Name Tags

CURRICULUM VITAE

NAME	Panit Chancharoonpong
DATE OF BIRTH	21 DECEMBER 1994
BIRTH PLACE	Bangkok
ADDRESS	Bangkok, Thailand
EDUCATION	Bachelor' degree in Electrical and Mechanical manufacturing engineering
WORK EXPERIENCE	- Mechanical Engineer - Research assistance at Centre of Excellence on enVironmental strategy for GREEN business (VGREEN)
PUBLICATION	Publication in Journal of Cleaner Production, Title "Life Cycle Assessment and eco-efficiency of high value-added riceberry rice products to support Thailand 4.0 policy decisions" Publication in conference abstract book EcoBalance 2020, Title "Environmental and economic performance improvement of a high value-added Thai Riceberry product"
SCHOLARSHIP	National Science and Technology Development Agency under the Thailand Advanced Institute of Science and Technology and Tokyo Institute of Technology (TAIST-Tokyo Tech) Program (Grant No. SCA-CO-2561-8183-TH). and NSTDA (National Science and Technology Development Agency) Research Chair Grant program under the sub-project entitled “Marketing strategies for organic rice & Innovative riceberry white rice and snack products with high nutritional and low carbon footprint values for niche markets” of the overall project entitled “Network for Research and Innovation for Trade and Production of Sustainable Food and Bioenergy” (Grant No. FDA-CO-2559-3268-TH).