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Energy usage and greenhouse gas emissions associated with tea and rubber manufacturing processes in Sri Lanka

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ABSTRACT

The objective of this study was to analyze the greenhouse gas (GHG) emissions associated with energy usage in tea and rubber industries in Sri Lanka. The scope of the study covered GHG inventory analysis of carbon dioxide, methane and nitrous oxide emissions associated with tea and rubber products, considering a life cycle approach starting from the plantations to the processed products. The functional units of tea and rubber products were 'one metric ton of tea' and 'one metric ton of dry rubber content (DRC)' respectively. Total GHG emission ranged from 514.27 ± 68.66 (high-grown) to 603.10 ± 191.58 (Uva) kg CO_2e ton^{-1} of made tea and the emissions were not statistically significant ($p > 0.05$; ANOVA and Tukey's multiple comparison tests) among the four tea growing regions, namely, high-grown, mid-grown, low-grown and Uva regions. The electricity consumption contributed 63% of the GHG emissions in tea industry and the rest of the emissions were from fossil fuel (23%) and biomass (14%) usage. GHG emissions associated with rubber plantations were 155.6 ± 47.4 kg CO_2e per ton of DRC. GHG emissions in raw rubber processing factories of crepe and ribbed smoked sheet (RSS), centrifuged latex and technically specified rubber (TSR) were 168.6 ± 44.1, 125.1 ± 24.8 and 375.60 kg CO_2e per ton of DRC respectively. GHG emissions associated with latex based and dry rubber based industries were 1472.1 ± 1011.8 and 1801.23 ± 360.26 kg CO_2e per ton of DRC respectively. The main source of GHG emissions in rubber industry was the use of grid electricity. GHG emissions associated with electricity usage in rubber plantations, crepe and RSS, centrifuged latex, TSR, latex based and dry rubber based industries were 15%, 80%, 42%, 53%, 75% and 52% respectively and the remaining emissions were from diesel, biomass, and fuel oil usage. Fuel switching in the manufacture of dry rubber based products has contributed to mitigation of GHG emissions by about 80%.

1. Introduction

Tea and Rubber products have been the main export agricultural products in Sri Lanka for more than 100 years. Until the recent past, tea was the main foreign income source of the country and rubber was in the second place. Even now these two industries are among first five foreign income sources. Sri Lankan tea is a famous beverage all around the world and Sri Lanka produces high-quality natural rubber. The aim of this study was to quantify the GHG emissions associated with energy usage in the industries relevant to tea and rubber crops of Sri Lanka. Currently, tea and rubber industries source raw material locally and export high-quality raw material and value-added products. Since both industries manufacture their products for the competitive export market, industries are now keen in reducing their products' life cycle GHG emissions through manufacturing low carbon- and carbon neutral products. Even

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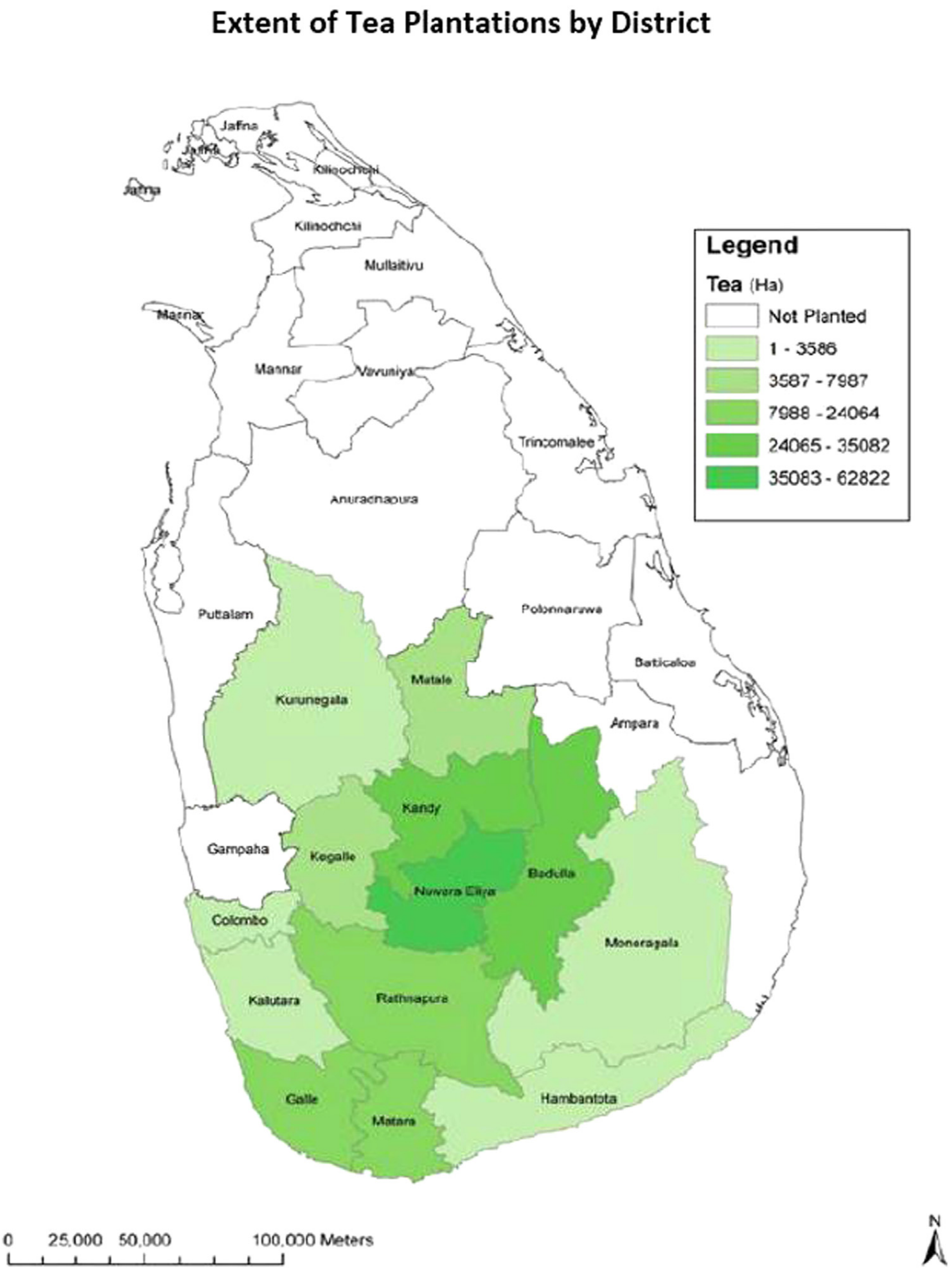

Fig. 1. Tea growing regions in Sri Lanka.

though the industries want to minimize the products' life cycle GHG emissions, industries lack the expertise and baseline information on their existing GHG emissions levels. The outcome of this research will provide a solid baseline for industries to develop manufacturing strategies for low carbon- and carbon neutral products. Further, the information will be used for National GHG Inventory preparations activities, industry, energy and climate-related strategic planning and policy development processes; and further research on product life cycle analyses in agriculture and industries.

Sri Lanka has produced 328,400 metric tons of tea on an area of 203,000 ha and earned 1414 million USD in 2012 (MPISL, 2013). Sri Lankan tea is mainly categorized based on the elevation where the crop is grown (e.g. high grown, medium grown and low grown) and tea is cultivated in 14 districts (Fig. 1). In Sri Lanka, tea is cultivated and processed by state plantation companies, regional plantation companies (private sector), small-scale tea holders and entrepreneurs. State plantation companies and regional plantation companies manage large tea estates which have an extent of 200–500 ha and estate-owned tea processing factories. Some estate owned tea processing factories process green leaf which is brought from other estates (known as *inter-estate* leaf) and small-scale tea holders (*bought* leaf). Thus, *bought* leaf processing factories are operated by entrepreneurs who buy green leaf from small tea holders.

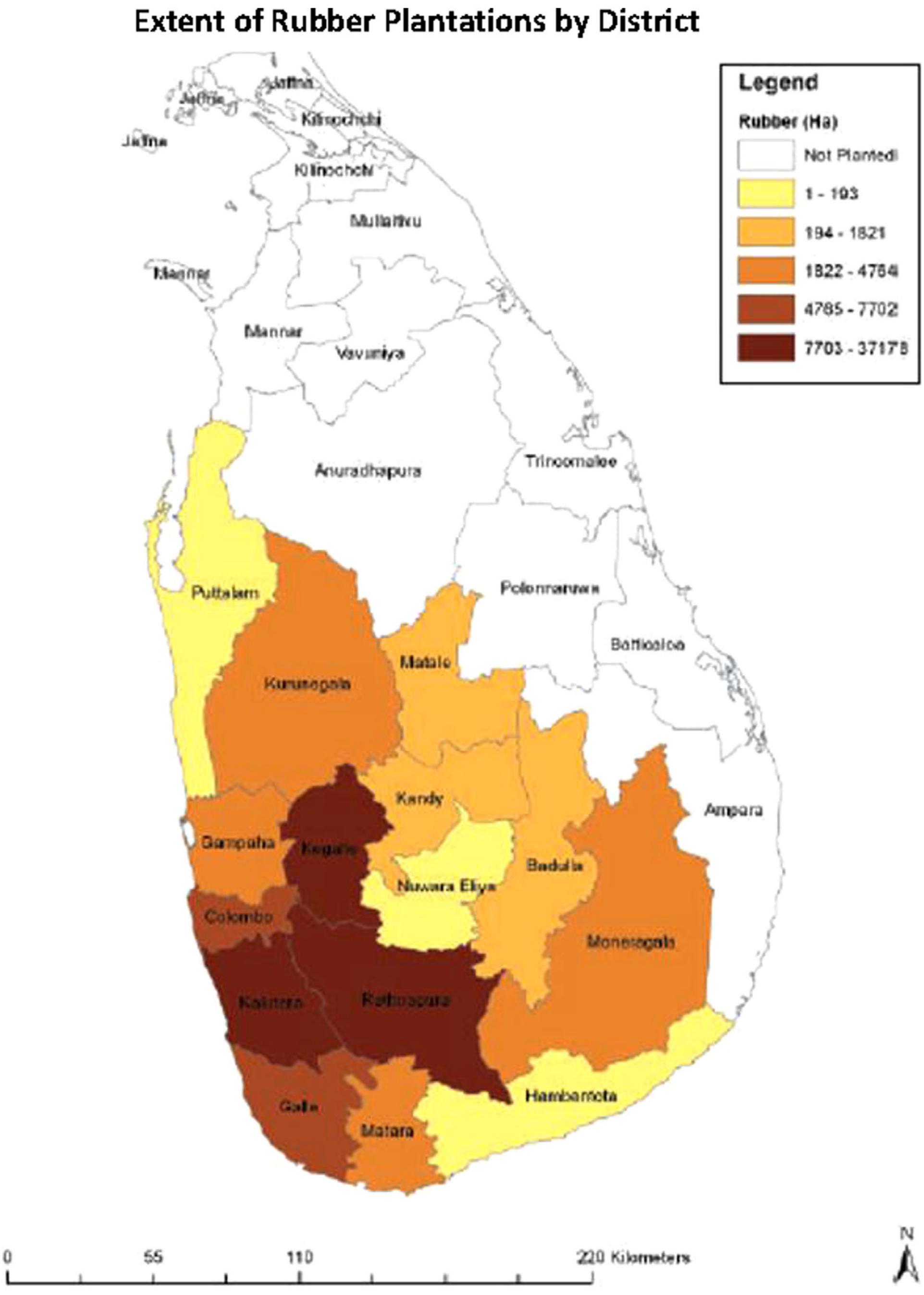

Fig. 2. Rubber growing regions in Sri Lanka.

Sri Lanka is one of the leading countries manufacturing high-quality natural rubber and value-added rubber products. The country produces about 152,100 metric tons of natural rubber per year, which is about 0.68% of global natural rubber production. Total rubber cultivation extends over 130,800 ha in 14 rubber growing districts (Fig. 2), out of which 104,200 ha are under tapping. Sri Lanka exports about 37,380 metric tons of rubber as raw rubber products and uses about 110,300 metric tons of rubber for manufacturing export-oriented value-added rubber products and local consumption. Rubber exports include raw rubber products (i.e. crepe, ribbed smoked sheet (RSS), concentrated latex and technically specified rubber (TSR), semi-processed rubber (reclaimed, compounded, etc.) and finished products (i.e. solid tire, pneumatic tire, dipped products such as gloves, foam rubber products, industrial commodities and household products). The rubber industry of Sri Lanka earned 981 million USD in 2012 (MPISL, 2013).

The main raw material sources of these two industries are commercial tea and rubber plantations. Both types of plantations use purchased grid electricity, diesel and petrol as the main sources of energy for plantation management activities.

In the tea industry, diesel is the source of energy used in transporting green leaf from plantations to tea processing factories. Purchased grid electricity, biomass, and diesel are the main sources of energy in tea processing factories. Diesel is also being used for transporting biomass (as a source of thermal energy) to the factories from different sources. Purchased grid electricity was generated mainly from hydro power, thermal power, and non-conventional renewable energy sources. Contributions of thermal energy generation to national grid electricity were 71%, 40% and 62% in the year 2012, 2013 and 2014 respectively.

In the rubber industry, diesel is the only energy source for transporting natural rubber latex from plantation to raw rubber processing factories and then transporting raw rubber products from raw rubber processing factories to rubber product manufacturing factories. In the raw rubber processing factories, purchased grid electricity and diesel are the two sources of energy. In rubber latex centrifuging industries, purchased grid electricity and diesel usage for latex transportation were the main energy sources. Crepe and RSS rubber factories use purchased grid electricity for milling operations and biomass for drying purposes. Value-added rubber products manufacturing industries mainly use purchased grid electricity, fuel oil, diesel, and biomass (RRISL, 2003).

Life cycle assessment (LCA) is considered one of the best approaches to evaluate the environmental impact of products. The LCA approach consists mainly of four phases, namely, goal and scope definition, life cycle inventory (LCI) preparation, life cycle impact assessment (LCIA) and life cycle interpretation (The International Standards Organisation (2006a). In the LCA, life cycle impact to the environment is mainly defined as midpoint impact categories and end-point impact categories (European Commission, 2010). The climate change impact of products has been assessed in many studies to date; however, other impact categories have also been considered (Roy et al., 2009).

Assessment focus, system boundary and impact categories have been widely varied in different studies and most of the studies have covered the life cycle phases from cradle to gate (both farm gate and factory gate) and exempted the distribution, consumption and disposal phases due to lower importance (based on the purpose of the study) and complexity of inventory preparation. In agriculture based product manufacturing systems, GHG emissions associated with energy usage have been considered as the main scope of many studies and other GHG emitting sources such as fertilizer applications and waste management have also been incorporated in several studies (Kodithuwakku Arachchige et al., 2015). In Sri Lanka, a comprehensive life cycle assessment of GHG emissions has not yet been carried out for either the tea or the rubber sector.

The objective of this study was to quantify the greenhouse gas emissions associated with energy usage in the tea and rubber sectors of Sri Lanka and identify measures to reduce associated GHG emissions. The study covered emissions associated with tea and rubber estates and factories managed by plantation companies and individuals.

2. Material and methods

2.1. Goal and scope

The goal of the study was to quantify and compare GHG emissions associated with energy usage in tea and rubber industries in Sri Lanka and identify significant GHG emitting sources and phases in the product life cycle from raw material extraction (i.e. tea and rubber plantations) to manufacturing. The study was a partial life cycle assessment which covered phases such as raw material extraction, pre-processing, transportation and product manufacturing. It also considered GHG emissions associated with energy usage only.

2.1.1. System boundary

The study covered GHG emissions associated with energy usage by both tea and rubber industries from plantations to product dispatch.

The system boundary of the tea industry covered GHG emissions associated with energy usage at tea plantations (which are managed by plantation companies), transportation of green leaf, tea processing, and bulk packaging. Energy sources in tea plantations are; purchased grid electricity from the national supply, diesel, and petrol. Diesel is used as to transport green leaf from tea plantations to the tea processing factories. In the tea processing factories, purchased grid electricity, diesel for standby generators and biomass for tea dryers are the main energy sources. Diesel is used for transporting biomass from different sources to tea processing factories.

The system boundary of the rubber industry covered GHG emissions associated with energy usage on the rubber plantations (which are managed by plantation companies), transportation of rubber latex, processing of intermediate rubber products (i.e. raw rubber products which are used as raw materials for manufacturing value-added rubber products), namely, crepe, RSS, TSR and centrifuged latex and finally the manufacture of value-added rubber products. The system boundary in the rubber plantations covered GHG emissions associated with purchased grid electricity, diesel and petrol usage for plantation management activities and transportation of latex. Rubber trees are grown mainly for natural rubber latex rather than rubber wood which is considered as a by-product which is harvested at the age of 25–30 years when the tree becomes unproductive in terms of rubber latex. One hundred percent of GHG emissions were associated with rubber latex production. In the intermediate and value-added rubber product manufacturing factories, the system boundary covered GHG emissions associated with electricity, diesel, fuel oil and biomass usage for factory operations and transportation of natural rubber and biomass. Rubber is cultivated by both regional plantation companies and small rubber landholders. Management practices of rubber plantations slightly vary among the different regional plantation companies, geographical regions, and among rubber small landholders. Crepe and RSS are manufactured in factories located in rubber plantations. Production mix (crepe and RSS) varies based on the demand and market price. RSS is also manufactured using a manual process at domestic level by rubber small landholders.

Centrifuged latex is mainly used for manufacturing dipping and foam rubber products. Latex centrifuging factories are not located in each rubber plantation; it may be one or two factories in a sub-region depending on the availability of natural rubber latex. Skim rubber is a by-product of latex centrifuging process and effluent (wastewater) is treated prior to discharge. TSR is processed using field coagula such as earth scrap (scrap rubber mixed with soil), tree laces, bark scrap and cup lump (coagulated rubber in the latex collecting cup).

2.1.2. Functional unit

One metric ton of tea (also called as 'made tea' which was the final product) was considered as the functional unit of the tea industry. In the rubber industry, one metric ton of dry rubber content (DRC) was considered as the functional unit. The study considered annual activity data for the years 2012, 2013 and 2014 in both the tea and rubber sectors and results of the three years were averaged to minimize annual and seasonal variations.

2.2. Inventory analysis and impact assessment

A GHG inventory associated with energy usage was prepared considering energy usage of activities within each phase of the life cycle. Activity data for plantations, leaf and latex transportation and factory operations were gathered separately.

The emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) associated with tea and rubber plantations and processing per functional unit were calculated separately and then converted into CO_2 equivalent (CO_2e) units using the global warming potential of each gas.

3. Estimation of GHG emissions

3.1. GHG emissions calculation

Scope-1 and scope-2 GHG emissions, which covered direct GHG emissions within the system boundary and indirect GHG emissions from purchased energy sources were calculated according to the GHG emission calculation protocols (WBCSD et al., 2011; The British Standards Institution, 2011) and guidelines (IPCC et al., 2006) using Tier-1 default emission factors, country-specific grid emission factors (Table 1; (SLSEA, 2016) and the global warming potential of each greenhouse gas (Table 2; UNFCCC, 2016). Purchased electricity was generated mainly from hydro power, thermal power and non-conventional renewable energy sources. The Grid Emission Factor was calculated only for the electricity generated at thermal power plants. The contribution of thermal energy to the national grid electricity varied annually with the hydro power capacity. The following equation was used for the calculations.

$$E_{x,i} = \sum_{i} (A_i x EF_{x,i} x GWP_x) \quad (1)$$

Where $E_{x,i}$ is the emission of greenhouse gas x (x = CO_2, CH_4, and N_2O) from activity i. A_i is the activity data of activity i. $EF_{x,i}$ is the emission factor for greenhouse gas x associated with an activity i and GWP_x is the global warming potential of greenhouse gas x.

Activity data for three consecutive years from 2012 to 2014 were used for both industries for GHG inventory preparation. Results of three years were averaged to minimize annual and seasonal variations. Statistical data analyses were performed using R (Version 0.99.486 ©2009–2015 R-Studio Inc.).

3.2. Activity data: tea

Activity data for three consecutive years from the year 2012 onwards were gathered from 70 tea plantations and small-scale tea holders, 68 tea processing factories located in all the tea growing regions, namely, high grown, medium grown, low grown and Uva regions (Table 3).

Activity data in tea plantations included diesel and petrol usage for land preparation, collection and transport of green leaf to tea processing factories and management activities, and purchased grid electricity usage for estate offices and bungalows. Purchased grid electricity usage, diesel usage for standby generators and biomass transport, and biomass usage were the activity data gathered from tea processing factories (Table 3.).

Table 1
Grid emission factors of thermal power electricity generation in Sri Lanka.

Year	Grid Emission Factor (kg $CO_2(kWh)^{-1}$)	Thermal Fraction[a] (%)
2012	0.7350	71
2013	0.7092	40
2014	0.7210	62

[a] Percentage of electricity added to the national grid from thermal power plants.

Table 2
Global warming potential of GHGs.

Greenhouse Gas	Global Warming Potential[a]
Carbon Dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous Oxide (N_2O)	310

[a] 100-year time horizon.

Table 3
Tea activity data.

Activity Data	Unit	Mean			
		High Grown	Medium Grown	Low Grown	Uva Region
Plantations:					
Purchased Electricity	kWh(ton)$^{-1}$[a]	83.75 ± 36.89	105 ± 58.29	91.55 ± 76.31	133.55 ± 63.83
Diesel	l(ton)$^{-1}$	6.53 ± 2.50	7.15 ± 3.08	23.54 ± 21.06	6.89 ± 2.67
Petrol	l(ton)$^{-1}$	3.29 ± 1.69	5.43 ± 2.57	16.08 ± 12.24	5.44 ± 2.4
Green Leaf Transport:					
Diesel	l(ton)$^{-1}$	12.00 ± 5.45	21.41 ± 6.61	20.82 ± 13.78	29.55 ± 11.57
Tea Processing:					
Purchased Electricity	kWh(ton)$^{-1}$	776.15 ± 115.86	793.68 ± 137.87	721.42 ± 163.27	862.11 ± 290.31
Diesel (for generator)	l(ton)$^{-1}$	3.06 ± 0.46	0.0055 ± 0.0026	0.0043 ± 0.0015	0.0047 ± 0.0025
Biomass	ton(ton)$^{-1}$	2.42 ± 0.49	2.92 ± 0.39	2.63 ± 0.601	2.69 ± 0.99
Diesel (biomass transport)	l(ton)$^{-1}$	11.89 ± 5.93	5.44 ± 5.06	4.63 ± 3.41	3.88 ± 2.74

[a] per ton of tea (the final product).

3.3. Activity data: rubber

In the rubber sector, activity data for three years were gathered from 2012 onwards from 35 rubber plantations, 21 crepe and RSS rubber processing factories, five concentrated latex processing factories, and one TSR factory which are located in Kalutara, Colombo, Kegalle, Galle, Ratnapura, and Badulla districts. In the value-added rubber product manufacturing sector, activity data were gathered from seven latex-based rubber product manufacturing factories and five dry rubber products manufacturing factories in western and southern provinces (Table 4).

Activity data in rubber plantations included diesel and petrol usage for tillage, the transport of rubber latex to central collection tanks and management activities, and purchased grid electricity usage for estate offices and bungalows. Diesel for transporting rubber latex to raw rubber processing mills, purchased grid electricity usage, diesel usage for standby generators and biomass usage were the activity data gathered from raw rubber processing factories. Activity data gathered from value-added rubber product manufacturing factories were; purchased grid electricity usage, diesel usage for internal transport and material handling activities, diesel usage for the standby generator, fuel oil used for thermal energy generation, biomass usage for thermal energy generation and transportation of biomass from the sources to the factory.

4. Results

In the tea industry, tea (also called as 'made tea') in bulk packaging was selected as the final product and in the rubber industry, several products such as intermediate raw rubber products and value-added rubber products were selected. GHG emissions of local tea and rubber industries largely depend on purchased grid electricity and thermal energy sources such as biomass and fossil fuel (i.e. diesel and fuel oil). Almost all the tea manufacturing factories have switched to biomass from conventional fossil fuel usage as the source of thermal energy. However, in the rubber industry, all the raw rubber processing industries use biomass as the thermal energy source at smoke houses. Value-added rubber product manufacturing industries use both biomass and fossil fuel to fulfill their thermal energy requirement.

4.1. The tea industry

GHG emissions associated with energy usage in the tea sector are summarized in Table 5. The differences in GHG emissions associated with energy usage among the four tea growing regions were not statistically significant ($F (3.54) = 2.058$), $p > 0.05$ (ANOVA). Among the four regions, highest (603.10 ± 191.58 kg CO_2e ton^{-1}) and lowest (514.27 ± 68.66 kg CO_2e ton^{-1}) GHG emissions were recorded in low grown and high grown regions respectively.

The GHG emissions associated with energy usage in plantations were significantly different, especially as the low-grown region had much higher emission compared to the other regions ($F (3,42) = 6.50$, $p < 0.05$ (ANOVA); $p < 0.05$ (Tukey's multiple comparison tests)). The usage of all three energy sources in plantations, namely, purchased grid electricity, diesel, and petrol, was higher

Table 4
Rubber sector activity data.

Activity Data	Unit	Mean
Plantations:		
Purchased Electricity	kWh (ton DRC)$^{-1}$	58.1 ± 36.4
Diesel use	l (ton DRC)$^{-1}$	39.4 ± 17.1
Petrol use	l (ton DRC)$^{-1}$	6.7 ± 4.7
Raw Rubber Processing Factories:		
Crepe and RSS:		
Electricity	kWh (ton DRC)$^{-1}$	386.6 ± 145.4
Biomass use	ton (ton DRC)$^{-1}$	0.97 ± 0.2
Diesel use for standby generator	l (ton DRC)$^{-1}$	2.2 ± 3.4
Centrifuged / Concentrated Latex:		
Electricity	kWh (ton DRC)$^{-1}$	130.1 ± 31.8
Diesel use for transport	l (ton DRC)$^{-1}$	22.2 ± 9.8
Diesel use for standby generator	l (ton DRC)$^{-1}$	3.3 ± 5.4
Technically Specified Rubber (TSR)[a]:		
Electricity	kWh (ton DRC)$^{-1}$	382.4
Diesel use for dryer and transport	l (ton DRC)$^{-1}$	65.7
Value-added Rubber Product Manufacturing Factories:		
Concentrated Latex (CL) Based Products:		
Electricity	kWh (ton DRC input)$^{-1}$	2606.9 ± 952.4
Diesel use for CL transport	l (ton DRC)$^{-1}$	10.1 ± 14.6
Diesel use for standby generator	l (ton DRC input)$^{-1}$	3.6 ± 3.1
Fuel oil use for thermal energy	l (ton DRC input)$^{-1}$	43.9 ± 16.8
Biomass use for thermal energy	ton (ton DRC input)$^{-1}$	7.7 ± 4.8
Diesel use for biomass transport	l (ton DRC input)$^{-1}$	21.9 ± 24.1
Dry Rubber Based Products:		
Electricity	kWh (ton DRC input)$^{-1}$	2311.7 ± 768.8
Diesel use for DR transport	l (ton DRC)$^{-1}$ (year)$^{-1}$	9.4 ± 5.0
Diesel use for standby generator	l (ton DRC input)$^{-1}$	4.3 ± 4.5
Fuel oil use for thermal energy	l (ton DRC input)$^{-1}$	279.4 ± 63.5
Biomass use for thermal energy	ton (ton DRC input)$^{-1}$	4.7 ± 1.2
Diesel use for biomass transport	l (ton DRC input)$^{-1}$	22.2 ± 3.4

[a]Data from a single factory.

Table 5
GHG emissions in the tea industry.

GHG Source	Kg CO_2e per ton of tea			
	High Grown Mean	Medium Grown Mean	Low Grown Mean	Uva Region Mean
Plantations:				
Purchased Electricity	33.68 ± 14.83	42.05 ± 23.43	65.37 ± 59.27	53.88 ± 25.65
Diesel	18.41 ± 7.05	20.15 ± 8.69	66.38 ± 59.39	19.43 ± 7.53
Petrol	7.8 ± 4.01	12.87 ± 6.09	38.11 ± 29.01	12.89 ± 5.69
Green Leaf Transport:				
Diesel	33.84 ± 15.37	60.38 ± 18.64	58.71 ± 38.86	83.33 ± 32.63
Tea Processing:				
Purchased Electricity	307.76 ± 42.69	317.64 ± 59.98	284.74 ± 70.58	340.9 ± 113.15
Diesel (for generator)	8.51 ± 1.28	0.02 ± 0.01	0.01 ± 0.004	0.01 ± 0.01
Biomass (CH_4 and N_2O)	70.74 ± 13.13	85.18 ± 11.38	76.72 ± 17.53	78.47 ± 28.88
Diesel (biomass transport)	33.53 ± 16.72	15.34 ± 14.27	13.06 ± 9.62	10.94 ± 7.73
Total	514.27 ± 68.66	553.62 ± 108.34	603.1 ± 191.58	599.86 ± 135.06

in the low-grown region compared to other regions. GHG emissions associated with purchased grid electricity and petrol usage were limited to estate sector tea plantations and those were at a minimum level in small-scale tea holders where they do not have a infrastructure such as an estate office, bungalows or employees' quarters.

GHG emissions associated with diesel usage in leaf transportation from the tea plantations to the processing plants were not significantly different ($F (3,56) = 2.13$, $p > 0.05$) in all four regions, but the highest mean value (83.33 ± 32.63 kg CO_2e ton^{-1}) was recorded in Uva region. Three different leaf supply chains, namely, *estate-owned* leaf, *bought* leaf, and the combination of *estate-owned* and *bought* leaf were considered. The transport related emissions associated with these supply chains were estimated as 44.12 ± 24.21, 67.20 ± 66.01 and 93.52 ± 64.08 kg CO_2 ton^{-1} respectively.

The emissions associated with the different supply chains were significantly different especially because of the lower emissions associated with *estate-owned* leaf transport compared to the other two supply chains ($F (2,58) = 5.152$; $p < 0.05$). Tea processing

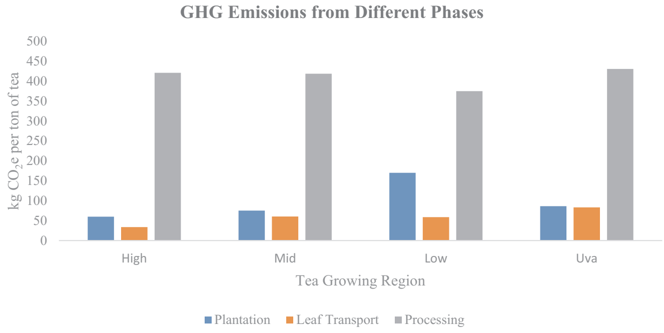

Fig. 3. GHG emissions from different phases in tea sector.

plants were distributed across each region where tea plantations and small tea holders were located. Large tea estates supplied green leaf to their own tea processing plants or the nearest tea processing plant. Small-scale tea holders supplied their green leaf to tea processing factories, which paid the highest rate per kilogram of green leaf in their region.

Amongst the three phases covered in the cradle to gate life cycle of tea, the highest GHG emissions were recorded in the tea processing phase in all four regions. GHG emissions from the tea processing phase were associated with purchased electricity usage, diesel usage for standby generation, methane and nitrous oxide emissions from biomass burning and diesel usage for biomass transport. Amongst all four regions, the highest (81.77%) and the lowest (62.10%) contributions were from high-grown and low-grown regions respectively.

GHG emissions associated with energy usage in tea processing were not significantly different ($F(3,57) = 2.01$, $p > 0.05$) amongst all four regions. Purchased electricity was the main source of GHG emissions in tea processing factories and on average it contributed 76% of total emissions associated with energy usage in tea processing. The emissions associated with the transport of biomass (as a thermal energy source) were significantly different amongst the four regions, especially as the high-grown tea region had much higher emissions in biomass transport compared to the other regions ($F(3,55) = 6.039$, $p < 0.05$ (ANOVA); $p < 0.05$ (Tukey's multiple comparison tests)). The wide range of distances covered in transportation (and associated fuel use) yielded relatively high standard deviations for the emissions associated with biomass and leaf transport in certain regions.

GHG Emissions from tea plantations and green leaf transport phases were mainly associated with fossil fuel usage. GHG emissions from green leaf transport were high in Uva region compared with the other two regions (Fig. 3).

Purchased electricity was the main source of energy in tea industry contributing more than 63% of GHG emissions; fossil fuel and biomass contributed 22.6% and 13.70% of the GHG emissions respectively. The grid emission factor (i.e. GHG emissions from purchased grid electricity generation) varied with the electricity generation mix (i.e. hydro and thermal) in the country.

4.2. The rubber industry

4.2.1. Emission from rubber plantations

Annual GHG emissions from rubber plantations were approximately 156.33 ± 48.9 kg CO_2e per ton of DRC (Table 6). The highest GHG emissions (116.0 ± 42.6 kg CO_2e per ton of DRC) were associated with diesel usage for plantation activities (i.e. land preparation and fertilizer transportation) and rubber latex transportation. The emissions associated with electricity and petrol usage were limited to estate sector rubber plantations and the emissions were at a minimum level in small-scale rubber holders having no estate office, bungalows or employees' quarters.

4.2.2. Emission from raw rubber processing factories

GHG emissions associated with crepe and RSS rubber, centrifuged latex and TSR production were 168.7 ± 44.1, 125.1 ± 24.8 and 375.6 kg CO_2e per ton of DRC respectively (Table 7). GHG emissions from grid electricity usage in crepe and RSS rubber factories were about 134.3 ± 44.7 kg CO_2e per ton of DRC. Electricity was mainly used for running rubber mills and the specific electricity consumption in producing a ton of crepe and RSS rubber varied from 176 to 534 kWh. Most of the crepe and RSS rubber factories are

Table 6
GHG emissions from rubber plantations.

Activity (GHG Emission Source)	GHG Emission (kg CO_2e (ton DRC)$^{-1}$) Mean
Plantations:	
Purchased Electricity	23.6 ± 15.3
Diesel use	116 ± 42.6
Petrol use	16 ± 11.3
Total Emission	**155.6 ± 47.4**

Table 7
GHG emissions from raw rubber processing factories.

Activity (GHG Emission Source)	GHG Emission (kg CO_2e (ton DRC)$^{-1}$) Mean
Raw Rubber Processing Factories:	
Crepe and RSS:	
Electricity	134.3 ± 44.7
Biomass use	28.4 ± 5.9
Diesel use for standby generator	5.8 ± 2.9
Total Emission	**168.7 ± 44.1**
Centrifuged / Concentrated Latex:	
Electricity	53.6 ± 13.2
Diesel use for transport	62.7 ± 27.6
Diesel use for standby generator	8.8 ± 14.6
Total Emission	**125.1 ± 24.8**
Technically Specified Rubber (TSR):	
Electricity[a]	199.6
Diesel use for dryer and transport[a]	176
Total Emission	**375.6**

[a] Data from one factory.

in rubber estates and emissions associated with rubber latex transport is at a minimum level.

The electricity usage in factory and fuel use in transportation of latex from rubber estates to factories were the main GHG-emitting sources in centrifuged latex producing factories. GHG emissions associated with electricity usage and transportation were 53.6 ± 13.2 and 62.7 ± 27.6 kg CO_2e per ton of DRC respectively.

GHG emissions from TSR production were at a higher level compared to crepe and centrifuged latex production. TSR is mainly produced with rubber that is polluted and contaminated with soil and other foreign matter. The Manufacturing process uses more cleaning and milling operations.

4.2.3. Emissions from value-added rubber product manufacturing factories

Grid electricity usage was the main source of GHG emissions (1118.2 ± 988.1 kg CO_2e per ton of DRC input) in latex based product manufacturing industries (Table 8). The second highest GHG emitting source was the use and transport of biomass. GHG emissions associated with the use and transport of biomass were 167.5 ± 79.6 and 60.5 ± 65.9 kg CO_2e per ton of DRC input respectively. GHG emissions associated with biomass transportation significantly varied due to several factors including the distance of transport, quantity transported and the variety of wood and type of biomass (logs, off-cuts, and sawdust). The GHG emissions associated with fuel oil use were at a lower level in the rubber industry due to fuel being switched from fuel oil to biomass during the last decade.

In the dry rubber value-added product manufacturing industry sector, GHG emissions associated with grid electricity use (946.7 ± 319.4 kg CO_2e per ton of DRC input) was the highest emission source. This industry still uses fuel oil as the main thermal

Table 8
Emissions from value-added rubber product manufacturing factories.

Activity (GHG Emission Source)	GHG Emission (kg CO_2e (ton DRC input)$^{-1}$) Mean
Value-added Rubber Product manufacturing:	
Concentrated Latex (CL) Based Products:	
Electricity	1118.2 ± 988.1
Diesel use for CL transport	28.5 ± 19.4
Diesel use for standby generator	9.95 ± 8.9
Fuel oil use for thermal energy	125.9 ± 48.5
Biomass use for thermal energy	167.4 ± 79.6
Diesel use for biomass transport	60.5 ± 65.9
Total Emission	**1472.1 ± 1011.8**
Dry Rubber Based Products:	
Electricity	946.7 ± 319.4
Diesel use for DR transport	26.5 ± 13.9
Diesel use for standby generator	11.56 ± 5.2
Fuel oil use for thermal energy	816.5 ± 185.6
Total Emission	**1801.2 ± 360.3**
Biomass use for thermal energy[a]	101.94
Diesel use for biomass transport[a]	62.66

[a] Data from one factory and those values were not included for GHG emissions estimation in Dry Rubber Based Products.

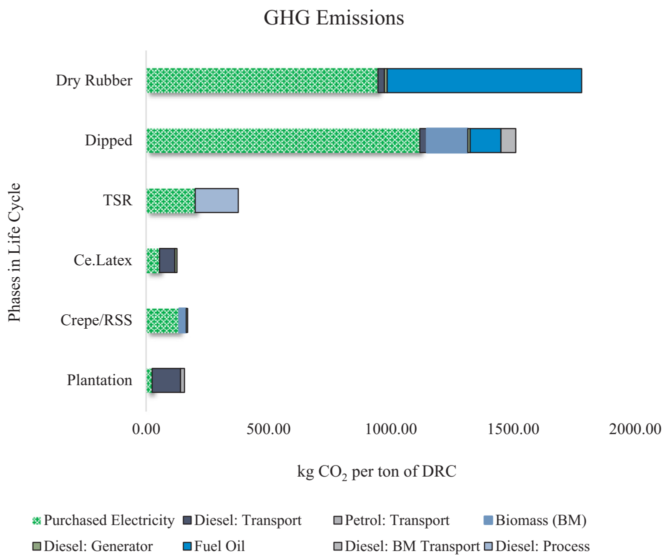

Fig. 4. GHG emissions from different phases in the rubber sector. Ce.Latex: Centrifuged Latex.

energy source and some factories are in the process of switching to renewable fuel sources such as biomass.

GHG emissions associated with fuel oil use were about 816.5 ± 185.6 kg CO_2e per ton of DRC input in factories which used 100% fuel oil for thermal energy generation.

4.2.4. Total GHG emissions

Total GHG emissions associated with energy usage in the rubber sector involved the three phases of its life cycle from rubber plantations to value-added rubber product manufacturing. GHG emissions associated with value-added rubber product manufacturing recorded comparatively higher values in latex based products (1472.1 ± 1011.8 kg CO_2e per ton of DRC input) and dry rubber based products (1801.2 ± 360.3 kg CO_2e per ton of DRC input) than the estimated values in rubber plantations and raw rubber processing (Fig. 4). The total GHG emissions associated with energy usage in latex based products included GHG emissions from rubber plantations, centrifuged latex processing and value-added latex based product manufacturing. Similarly, GHG emissions associated with energy usage in dry rubber based products consisted of GHG emissions from rubber plantations, RSS and TSR processing and value-added dry rubber based product manufacturing.

4.3. Comparison of tea and rubber industries

In the tea and rubber industries, four products were selected to compare the GHG emissions associated with cradle to gate energy usage: made tea, crepe rubber, latex based value-added products and dry rubber based value-added products. Sri Lanka mainly exports made tea in bulk, crepe rubber in bulk as a raw material and value-added rubber products from two sectors namely, dry rubber based and latex based product manufacturing. Out of the tea and rubber industries, the highest GHG emissions were associated with value-added rubber products (Fig. 5). GHG emissions associated with purchased electricity was the main contributing source and it contributing more than 50% of the products' GHG emissions associated with energy usage.

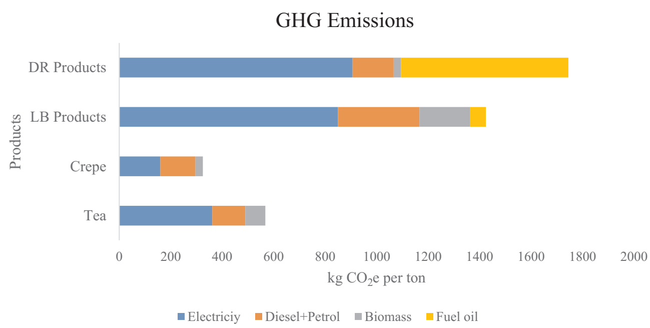

Fig. 5. GHG emissions from different tea and rubber products. DR Products: Dry Rubber Products, LB Products: Latex Based Products.

5. Discussion

Tea and rubber were introduced as large-scale plantations during the British colonial period. Both plantation sectors and processing industries, except value-added rubber product manufacturing industries, followed the traditional manufacturing practices and used old machinery and technologies which were introduced by the British. With the current global trend in sustainable consumption and production which has been practiced for about last 20 years (UNEP, 2015), the tea and rubber industries have been required to improve their socio-economic and environmental performance e.g. by reducing their impact on climate change, energy efficiency improvement, increasing the share of energy from renewables, enhancing biodiversity, practicing soil and water conservation, sound chemical management, etc.

The results of this study could be used by both industries in developing sustainability indicators incorporating energy usage, GHG emissions in different phases and product life cycle GHG emissions. The results provided information to set up baselines for monitoring and evaluating the environmental performances such as setting up of internal and external benchmarks and even regional benchmarks.

Since the products are manufactured for the competitive export market, both industries are currently keen to report their product's carbon footprint (i.e. GHG emissions). However, the industries lack required knowledge and background information, especially in relation to the upstream processes of the products' lifecycle and accurate activity data and emission values. This study provides information on GHG emissions in different phases from plantation to finished product manufacturing and the GHG emission associated with different energy sources such as purchased grid electricity and usage of fossil fuel and biomass within each phase of the product's life cycle.

The results of this study would be useful for researchers and sector experts who wish to expand the scope of the study and incorporate GHG emissions other than energy usage, such as soil carbon stock changes, biomass carbon sequestration, GHG emissions from nitrogen fertilizer application, urea and dolomite application and the impact of the unsustainable use of biomass (as a thermal energy source) on carbon sequestration.

Since tea and rubber industries have a significant contribution on the country's economy, national policies and strategies would be developed to improve the sustainability of these industries, especially focusing on energy usage and GHG emissions which impact on climate change. The results of the study have provided baseline quantitative information which would be necessary for macro-level decision making.

Results from tea and rubber industries clearly indicate the opportunities for GHG mitigation in future. Purchased grid electricity contributed 55% of total GHG emissions associated with energy usage on average in all four regions and indicated highest GHG mitigation potential in the tea industry. GHG mitigation would be achieved by energy efficiency improvement in the tea processing factories, increasing the renewable energy (i.e. solar PV, hydro, wind) share, etc. In the rubber industry, mitigation opportunities are mainly available in value-added rubber product manufacturing. Fuel switching in many value-added rubber product manufacturing industries has helped mitigate the GHG emissions associated with fuel oil usage although the intended purpose might not have been the reduction of GHG emissions. The contribution of purchased grid electricity to total GHG emissions varied from year to year based on fluctuations in the grid emission factor, which depends on the combination (i.e. mix) of power generation sources within the country in any given year.

Life cycle analysis studies on tea and rubber products have been carried out in Sri Lanka and other countries (Doublet and Jungbluth, 2010); however, in-depth analysis of GHG emissions associated with the cradle to gate life cycle of the tea and rubber industries are rare (AIT, 2002). A study done on the economic, social and environmental impacts in local tea industries (Munasinghe et al., 2017) considered the energy usage and GHG emissions in the cultivation, transport and processing phases of the life cycle in only three regions, namely, high, medium and low grown regions. However, it provided the results for two products, orthodox and CTC tea and considered only nine sample tea estates and factories. Certain studies focusing on energy demand (Silva, 1996) and the environmental impact (Dhanapala and Wijayatunga, 2002) considered only the renewable energy sources for tea processing. The recent study by Hasanthi and Amarasinghe (2015) carried out considering one tea estate and one factory for development of a carbon emission calculating model might not reflect the exact situation of the local tea industry. In relation to the rubber industry, similar studies have been carried out in Thailand (Jawjit et al., 2010; Petsri et al., 2013) but not in Sri Lanka.

6. Conclusion

Tea plantations, green leaf transportation and tea processing are the phases of cradle to gate life cycle of made tea. Tea processing phase had the highest contribution to GHG emissions and it varied from 62% to 82% in different tea growing regions. Purchased electricity was the main GHG emitting energy source along the cradle to gate life cycle of made tea and contributed more than 63% of the energy-related GHG emissions in all tea growing regions.

Rubber Plantations, rubber latex transportation, raw rubber processing (four products, namely, crepe, RSS, TSR and centrifuged latex) and value-added rubber product manufacturing (both latex based and dry rubber based products) are the phases of cradle to gate life cycle of rubber products. The value-added rubber products manufacturing phase contributed 84% and 85% of GHG emissions in latex based and dry rubber based product manufacturing processes respectively. Purchased electricity was the main GHG emitting energy source along the cradle to gate life cycle of both dry rubber based and centrifuged latex based rubber products and the latter products contributed 52% and 68% of the energy-related emissions respectively.

GHG emission reduction could be achieved through improving electrical energy efficiency. However, due to the grid emission factor variations, energy efficiency improvement would not reflect the reduction of GHG emissions associated with purchased electricity. GHG emissions associated with purchased electricity varied with grid emission factor. The grid emission factor ranged from zero (when total electricity generation is from 100% hydro and renewable energy sources) to about 0.92 kg CO_2e per kWh (when the total electricity generation is from 100% thermal power plants).

Fuel switching in the dry rubber based product manufacturing sector has been responsible for about 80% of the reduction of GHG emissions in this sector. Most value-added rubber product manufacturing factories used fuel oil as the main source of thermal energy and now these industries are switching to biomass. Such a switch would reduce both the cost of energy and the GHG emissions associated with thermal energy usage.

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