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Energy Demand and Greenhouse Gases Emissions in the Life Cycle of Coffee Harvesters

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Besides global climate changes and the exhaustion of natural resources, the concern about energy resources is one of the main challenges of 21st century. The growing population and, consequently, the increasing demand for food, fibre and bioenergy leads to an intensive use of machinery and equipment, resulting in more energy required and more greenhouse gases emitted. Materials and energy sources are consumed during a product's life cycle, so it is important to optimize them through reuse, recycling, reducing their demand and replacing them for more environmentally-friendly materials. In current agricultural production system, machinery is considered fundamental for biomass production. Energy analysis in agricultural machinery has been evaluated, but the indicators are mostly from the late 1960s and mostly were based on car industry. Studies on the embodied energy and emissions in agricultural mechanization should be carried out, due to the importance of food and bioenergy production systems in world economy. This study aimed to determine the inventory for materials, embodied energy and greenhouse gases emissions during the life cycle of a coffee harvester. Data were collected in a multinational manufacturer, in its unit located at Piracicaba municipality, State of São Paulo. For the coffee harvester, the consumption of the direct input used in the assembly phase and the input used in the maintenance phase were accounted. Input data were presented as materials flows, which were translated by their embodied energy indices and emissions factor, resulting in the embodied energy and greenhouse gases emissions required by the production system. Results presented the following embodied energy (67.05 MJ kg^{-1}) and greenhouse gases emissions (4.75 kg CO2e kg^{-1}).
Keywords: Life cycle assessment; sustainability; machinery.

1. Introduction

Energy is vital for the development of economies and societies and its demand is increasing globally (Abubakar and Umar, 2006), being mandatory to produce goods from natural resources and to provide services (Hinrichs and Kleinbach, 2009). Energy analysis regards the physical amounts involved in a process, measuring its energy content (Fluck and Baird, 1980). To evaluate a production process, the material flows converging into a product and wastes need to be determined (Dyer and Desjardins, 2006).

Differently from some industrial sectors (Nassim and Hassan, 2017; Wang and Ho, 2017), for agricultural machinery assembling, life cycle assessments determining embodied energy and greenhouse gas emissions are rare (Mantoam et al., 2014; Mantoam et al., 2016). Berry and Fels (1972) determined the embodied energy index (81.2 MJ kg^{-1}), based on the car industry from the late 1960s. Deleage et al. (1979) determined the index (75.0 MJ kg^{-1}) for tractors, due to different material quantities and proportions from car industry. Although recently, Mantoam et al. (2014) determined indices for sugarcane harvesters, finding values around 2.6 times greater than those determined by Berry and Fels (1972). But, sugarcane harvesters are machines with specific applications, being used around 3100 hours per year. The rate of use and the field conditions in which they operate result in a high requirement of maintenance and repair that their data on energy demand should not be applied to other kinds of machines. This study aimed at determining the energy demanded and

GHG emissions in the life cycle of coffee harvesters, due their importance on this crop in some tropical countries.

2. Material and methods

The coffee harvester evaluated presented a 3-cylinder Diesel engine (40 kW) and weighted 5600 kg. Its life cycle considered was 6000 h according to the manufacturer (Figure 1).
To evaluate the coffee harvester, this study applied a methodology to determine energy and emissions flows based on material demand of the assembly and maintenance phases of the machine life cycle (Mantoam et. al., 2014).

Figure 1: Coffee harvesting performed by the evaluated machine (CASE, 2014).

Fuel consumption on machinery operation was not considered, because it varies due to management decisions, field conditions and operator skills. The indices of embodied energy and GHG emission factors consider fossil energy and electricity required to obtain the materials that constitute the coffee harvester´s parts. For assembly phase, the directly used inputs refer to the parts supplied. These parts were grouped into material groups, for the importance of these materials in the machinery composition to be verified. Indirectly used inputs in assembly phase, such as electricity, liquefied petroleum gas, labor and water, were not assessed in this study due to lower embodied energy (Mantoam et. al., 2014).
The maintenance phase considered the inputs directly and indirectly used, which are necessary according to the recommendations of the manufacturer. This assumption was done to avoid discrepancies among farmers and other users, because they may adopt distinct maintenance strategies to their equipment.
Material flows were calculated and indices of energy embodiment for each input that were obtained in references (Table 1). So, they were used for the input energy flows to be determined. After the determination of the embodied energy in direct inputs and embodied energy in maintenance, their sum provides the embodied energy of the life cycle of a coffee harvester (Eq. (1)).

$$EE = \sum_{j=1}^{M} \sum_{i=1}^{N} (MF_{ij} * EI_i) \quad (1)$$

where: EE is total embodied energy in the inputs on tractor life cycle (MJ); MF is the material flow directly used in the parts assembled and maintenance into a tractor (kg, L, h); EI is the energy index of the material used (MJ kg^{-1}; MJ L^{-1}; MJ h^{-1}, Table 1); i = i-th material; j = j-th phases (maintenance, parts).
GHG emissions were determined also based on material flows and multiplyed them by the respective emissions factor (Table 1). After the determination of the emissions in direct inputs and emissions in maintenance, their sum provides the emissions of the life cycle of a tractor (Eq. (2)).

$$EM = \sum_{j=1}^{M} \sum_{i=1}^{N} (MF_{ij} * EF_i) \quad (2)$$

where: EM is total emissions in the inputs on tractor life cycle (kg CO_2eq.); MF is the material flow directly used in the parts assembled and maintenance into a tractor (kg, L); EF is the emissions factor of the material used (kg CO_2eq. kg^{-1}; kg CO_2eq. L^{-1}, Table 1); i = i-th material; j = j-th phases (maintenance, parts). After determination of the embodied energy and emissions, provides the embodied energy and emissions indicators, per life time, mass and engine power.

Table 1: Energy embodiment and emissions factor indices for inputs

Input	Embodied energy		GHG emission factor	
	Value	Unit	Value	Unit
Aluminum	231.00	MJ kg^{-1}	15.00	kg CO2e kg^{-1}
Anticorrosive fluid	2.29	MJ kg^{-1}	2.26	kg CO2e kg^{-1}
Brass	140.00	MJ kg^{-1}	2.82	kg CO2e kg^{-1}
Carbon steel	51.52	MJ kg^{-1}	3.19	kg CO2e kg^{-1}
Cellulose film	192.53	MJ kg^{-1}	1.60	kg CO2e kg^{-1}
Chemical powder ABC	2.48	MJ kg^{-1}	0.12	kg CO2e kg^{-1}
Copper	140.00	MJ kg^{-1}	6.00	kg CO2e kg^{-1}
Cotton synthetic fiber	45.29	MJ kg^{-1}	1.28	kg CO2e kg^{-1}
Diesel oil	47.78	MJ L^{-1}	2.60	kg CO2e L^{-1}
Ductile iron	32.66	MJ kg^{-1}	0.75	kg CO2e kg^{-1}
Engine oil	37.28	MJ L^{-1}	2.54	kg CO2e L^{-1}
Fiberglass & aluminum	0.79	MJ kg^{-1}	1.53	kg CO2e kg^{-1}
Fiberglass & polyester	0.79	MJ kg^{-1}	8.10	kg CO2e kg^{-1}
Grease	43.38	MJ kg^{-1}	5.30	kg CO2e kg^{-1}
Hydraulic oil	37.28	MJ L^{-1}	2.54	kg CO2e L^{-1}
Inorganic fiberglass	0.79	MJ kg^{-1}	1.53	kg CO2e kg^{-1}
Labour	2.20	MJ h^{-1}	-	-
Lead	17.31	MJ kg^{-1}	1.13	kg CO2e kg^{-1}
Lubricating oil	37.28	MJ L^{-1}	2.54	kg CO2e L^{-1}
Nylon 6.6	31.80	MJ kg^{-1}	6.50	kg CO2e kg^{-1}
Paint	2.48	MJ kg^{-1}	3.56	kg CO2e kg^{-1}
Paper	34.38	MJ kg^{-1}	1.50	kg CO2e kg^{-1}
Plate glass	30.22	MJ kg^{-1}	0.85	kg CO2e kg^{-1}
Polyethylene high density	52.45	MJ kg^{-1}	1.60	kg CO2e kg^{-1}
Polypropylene	110.16	MJ kg^{-1}	1.65	kg CO2e kg^{-1}
Polyurethane	110.16	MJ kg^{-1}	3.00	kg CO2e kg^{-1}
Polyurethane foam	110.16	MJ kg^{-1}	14.50	kg CO2e kg^{-1}
PVC	10.64	MJ kg^{-1}	3.00	kg CO2e kg^{-1}
ABS	1.24	MJ kg^{-1}	3.10	kg CO2e kg^{-1}
Rubber	88.00	MJ kg^{-1}	3.18	kg CO2e kg^{-1}
Solvent	2.48	MJ kg^{-1}	3.56	kg CO2e kg^{-1}
Stainless steel	81.77	MJ kg^{-1}	2.20	kg CO2e kg^{-1}
Steel wire	19.10	MJ kg^{-1}	2.83	kg CO2e kg^{-1}
Sulphuric acid	2.48	MJ kg^{-1}	2.26	kg CO2e kg^{-1}

Data collected by Mantoam et al. (2016).

3. Results and Discussion

Evaluations of material flows and GHG emissions were carried out for the assembling (Table 2) and maintenance (Table 3) phases.

3.1 Energy demand

Out of the total energy required by the coffee harvester to exist in its life cycle, 70.2 % is due to its assembling and constitution. The remaining 29.8 % is due to repair and maintenance. This is completely different for the situation described for sugarcane harvester by Mantoam et al. (2014), when 72.8 % of energy was required in by repair and maintenance. For the total life cycle of a coffee harvester 402.3 GJ were required.

For the assembling phase carbon steel represents 67.4 % of total energy and nylon 10.8 %, together both are responsible for 55 % of total energy demand in its life cycle.

Table 2: Material and energy demand and GHG emissions in the assembling phase of a coffee harvester

Components	Material flow		Energy demand		GHG emission	
	Qty	Unity	MJ	%	kg CO_2e	%
1.1 Metallic Ferrous Metals						
Carbon steel	3582.7	kg	184580.7	67.4	11428.8	57.1
Ductile iron	511.4	kg	16703.3	6.1	383.6	1.9
Steel wire	12.5	kg	237.9	0.1	35.2	0.2
1.2 Metallic Non-Ferrous Metals						
Aluminum	35.0	kg	8080.4	2.9	524.7	2.6
Lead	10.1	kg	2461.9	0.9	105.5	0.5
Copper	17.6	kg	175.2	0.1	11.4	0.1
Brass	0.2	kg	31.9	0.0	0.6	0.0
2 Non-Metallic Materials						
Nylon 6.6	932.2	kg	29642.9	10.8	6059.1	30.3
Rubber	226.3	kg	19914.4	7.3	719.6	3.6
Polyethylene high density	42.5	kg	2231.4	0.8	68.1	0.3
Polypropylene	9.1	kg	1002.5	0.4	15.0	0.1
Polyurethane foam	4.5	kg	495.7	0.2	65.3	0.3
Cellulose film	1.6	kg	300.3	0.1	2.5	0.0
Plate glass	6.8	kg	205.5	0.1	5.8	0.0
Polyurethane	1.0	kg	110.2	0.0	3.0	0.0
PVC (Poly Vinyl Chloride)	11.9	kg	126.4	0.0	35.6	0.2
Paper (printed news)	1.3	kg	43.0	0.0	1.9	0.0
Recycled ABS	1.0	kg	1.2	0.0	3.1	0.0
Sulphuric acid (H_2SO_4)	1.7	kg	4.2	0.0	3.8	0.0
Chemical powder ABC	3.2	kg	7.9	0.0	0.4	0.0
3 Lubricants and Fluids						
Hydraulic oil	158.0	L	5890.2	2.2	401.3	2.0
Diesel oil	14.0	L	668.9	0.2	36.4	0.2
Engine oil	15.3	L	568.5	0.2	38.7	0.2
Lubricating oil	7.5	L	279.6	0.1	19.1	0.1
Grease	3.7	kg	160.5	0.1	19.6	0.1
Anticorrosive fluid	1.0	kg	2.3	0.0	2.3	0.0
4 Paint and Solvent						
Paint	8.0	kg	19.8	0.0	28.5	0.1
Solvent	2.0	kg	5.0	0.0	7.1	0.0
Total			273951.8	100.0	20026.0	100.0

For maintenance, rubber is the most demanding material for 28 % of energy demand, followed by hydraulic oil (15 %), carbon steel (12 %), lubricant oil (11 %) and nylon (9 %). Five components respond to 75% of emissions in maintenance (~22 % of total).

3.2 GHG emissions

Unfortunately, for GHG emissions, there are not data from references for comparisons to be made, such as performed for energy demand. Assembling phase was responsible for 70.3 % of GHG emissions and maintenance for 29.7 %. The total emissions were 28500 kg CO_2e in its life cycle.

For the assembling phase carbon steel represents 57.1 % of total energy and nylon 30.3 %, together both are responsible for 62 % of total GHG emitted in its life cycle. In maintenance, nylon is the most demanding material for 29 % of GHG emissions, followed by hydraulic oil (16 %), rubber (15 %), carbon steel (12 %) and lubricant oil (11 %). Five components respond to 83 % of emissions in maintenance (~24 % of total).

Table 3: Material and energy demand and GHG emissions in the maintenance phase of a coffee harvester

Component	Material flow Qty.	Unity	Energy demand %	GHG emission %
1 Labor				
Labor	1393.8	h	2.4	-
2.1 Metallic Ferrous Metals				
Carbon steel	307.3	kg	12.3	11.6
Ductile iron	102.0	kg	2.6	0.9
2.2 Metallic Non-Ferrous Metals				
Aluminum	41.4	kg	7.4	7.3
3 Non-Metallic Materials				
Rubber	405.4	kg	27.8	15.2
Nylon 6.6	375.0	kg	9.3	28.8
Cellulose film	30.2	kg	4.5	0.6
Inorganic fiberglass	3.6	kg	0.0	0.1
Polypropylene	0.6	kg	0.1	0.0
4 Lubricants and Fluids				
Hydraulic oil	526.7	L	15.3	15.8
Lubricating oil	367.5	L	10.7	11.0
Engine oil	225.0	L	6.5	6.7
Grease	32.5	kg	1.1	2.0
Total (%)			100.0	100.0
Total (unit)			128.4 GJ	8474.1 kg CO_2e

For energy, the indices found were 67.05 MJ h^{-1}; 71.84 MJ kg^{-1} and 10.06 GJ kW^{-1} (Table 4), respectively relating energy by life cycle, mass and gross power. Its index by mass can be compared with those presented by Berry and Fels (1972) - 81.2 MJ kg^{-1}, and Deleage et al. (1979) - 75.0 MJ kg^{-1}, showing that the coffee harvester is energetically less intense per mass than tractors. Besides also being a harvester, its index is even further from the sugarcane one 202.6 – 204.3 MJ kg^{-1}, (Mantoam et al., 2014). Its level is comparable with a 246-kW tractor that presented 62.7 MJ kg^{-1} (Mantoam et al., 2016). More powerful tractors were more efficient than less power ones 98.7 MJ kg^{-1} (55 kW) to 72.1 MJ kg^{-1} (172 kW).

Table 4: Energy indicators for coffee harvester

Phase	Total value GJ	Energy indices MJ h^{-1}	GJ kW^{-1}	MJ kg^{-1}
Assembly	273.9	45.65	6.85	48.91
Maintenance	128.4	21.40	3.21	22.93
	402.3	67.05	10.06	71.84

For GHG emissions, the indices found were 4.75/ kg CO2e h^{-1}, 5.09 kg CO2e kg^{-1} and 712.50 kg CO2e kW^{-1} (Table 5), respectively relating GHG emissions by life cycle, mass and gross power. Comparing the emission by mass (4.7 kg CO2e kg^{-1}) with those found by Mantoam et al. (2016) for tractors 1.0 (55 kW, 2650 kg) to 2.4 (246 kW, 10950 kg), it is possible to state that coffee harvesting requires materials with highest emission levels than tractors.

Table 5: Indicators for GHG emissions for coffee harvester

Phase	Total value kg CO2e	GHG emission indices kg CO2e h^{-1}	kg CO2e kW^{-1}	kg CO2e kg^{-1}
Assembly	20026.0	3.34	500.65	3.58
Maintenance	8474.1	1.41	211.85	1.51
	28500.1	4.75	712.50	5.09

4. Conclusions

Comparisons among distinct agricultural machines show that they present distinct levels of energy demand and GHG emissions. So, using indices of other kinds of machinery may bring an incorrect evaluation of the production system evaluated.

In the assembling phase carbon steel and nylon are the most important causes of either energy demand or GHG emission.
In maintenance, nylon, rubber, hydraulic oil, carbon steel and lubricant oil are the most important causes. Nylon affects more GHG emissions while rubber is the main one for energy demand.
Adoption of other materials rather than nylon, carbon steel and rubber should be looked for, in order to increase the efficiency of the coffee harvester.

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