Material and energy flow analysis of the Malawian tea industry

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Abstract

This paper briefly reviews the material and energy flows of the Malawian tea industry, in order to identify opportunities and reduce its environmental impacts. The review also details the concept and methodology as well as studies on applications of material and energy flow analysis. Environmental impacts are calculated with a life cycle assessment approach, using CML methodology. Results indicate that green leaf consumption in the studied factories ranged from 4.19 to 6.33 kg green leaf/kg made tea (MT), with an average of 4.96 kg per kg of made tea compared to 4.5 and 4.66 kg green leaf for tea factories in Kenya and Sri Lanka, respectively. Average wood consumption in Malawian tea factories is 3.35 kg/kg made tea and specific water consumption ranged from 1.92 to 8.32 kg/kg MT. In addition, the average value of greenhouse gas (GHG) emissions for eight factories is 4.32 kg of CO_2-eq/kg MT as compared to 2.27 and 2.7 kg CO_2-eq/kg in similar factories in Kenya and Sri Lanka, respectively. The major sources emitting GHG are from boiler fuel combustion and stand-by diesel power generation system. The study indicates that global warming has the highest environmental impact (88%), followed by acidification (6%) and eutrophication (2%), whereas human toxicity is lowest (<1%). The findings demonstrate how MEFA provides early recognition of environmental problems and how it can be used to establish priorities for improving operations in the existing factories.

Keywords: Tea industry, Material flow analysis, Malawi, Environmental impact, Greenhouse gases

1.0   Introduction

Tea (*Camellia sinensis*) is an important agricultural and export cash crop in Malawi. Tea industry comprises 1.5 percent of Malawi's Gross Domestic Product (GDP), contributes 11 percent of the national employment, and accounts for 8 percent of foreign exchange earnings [1]. In addition, the industry generates about 40,000 to 60,000 direct jobs and 1.5 million indirect with annual turnover of sixteen billion Malawi Kwacha (US$86 million), making it the third largest export earner, after tobacco and sugar, respectively. Total land area under tea cultivation in the country is about 19,000 hectares and the annual tea production is approximately 46,500 tonnes, which accounts for 1.3 percent of total world production [2]. Malawi is now ranked the thirteenth largest tea growing country in the world and the third largest producer in Africa after Kenya and Uganda, respectively [3]. At present there are in total 21 tea factories in the country, most of which are located in the southern part of Malawi[4].

However, despite its importance to the economy, tea cultivation and processing significantly contributes to negative environmental impacts. Major impacts of the tea processing industry on the environment are related to habitat conversion, energy and agrochemical use, and wastewater generation [5]. More recent studies have shown that there is significant biodiversity loss due to conversion of forests into tea farms [6]. In addition to habitat conversion, logging of firewood from local forests needed for drying tea has led to deforestation. Since not all tea factories have sustainable plantations from which they would harvest wood fuel, natural forests remain the major source.

Tea factories also emit gaseous, liquid as well as particulate pollutants. The main sources of pollution are waste water from factory processes and exhaust fumes from boilers, standby generator sets and factory trucks that carry green leaf to the factory. Pesticides and chemical fertilizers are also sources of pollution. The environmental impacts of these pollutants vary. Waste water discharged from tea processing factories cause high levels of colour, chemical oxygen demand (COD), and biochemical

oxygen demand (BOD) [7], [8]. Pesticides and chemical fertilizers affect water quality and aquatic ecosystems. Exhaust fumes release carbon dioxide and nitrous oxides which are greenhouse gases that cause global warming, sulphur dioxide which is responsible for acid rain and particulate matter which affect human health. Tea factories are also energy intensive.

Material and energy flow analysis (MEFA) has been widely recognized as one important and necessary step for reducing the impacts of human activities on the environment [9], [10], [11]. MEFA utilises process material and energy input-output data to characterise the use and emission of materials within and between processes. All flows and indicators are measured in mass units, giving a physical quantification of the system's material requirements. Furthermore, it can be used to reduce the consumption of energy, raw material, water and discharge of effluents by pursuing systematically internal flows of energy and mass in production processes. MEFA is increasingly applied in the fields of industrial ecology, environmental management and protection, resource management, and waste management. It is also used as a basis for life cycle assessment, eco-balance, environmental impacts strategies [12]. Recently the methodology has been applied to optimise material flows and waste streams in production processes in different countries [13],[14],[15],[16]. However, to the best of the author's knowledge, there is surprisingly lack of published data and research on material and energy analysis of the tea industry.

The objective of this paper is to review the information available, introduce and discuss the applicability of MEFA approach to the Malawian tea industry. The study is the first step in developing MEFA methods to analyse and monitor the material and energy flows of the tea industry. The essence of this study is to identify improvement opportunities in the tea manufacturing process and reduce their environmental impacts while maximising economic, social and environmental benefits.

2.0 Material and energy flow analysis

2.1 Conceptual framework

Material and energy flow analysis (MEFA) is a systematic assessment of the flows and stocks of materials (including energy) within a system defined by space and time [9]. It is an analytical tool that examines the material stocks and flows coming into and out of a given system, and the resulting outputs from the system [10], [9], [17]. MEFA constitutes an important approach to track the use of materials and energy by socio-economy systems from extraction to manufacturing, to final uses and disposal of emissions and wastes. The material flow approach can be traced back to the second half of the nineteenth century [18], but current approaches rely on methods developed in the late 1960s and early 1970s [19]. The aim is to trace the physical flow of materials, products and wastes associated with particular economic activities. MEFA uses the principle of mass balancing to study how material and energy flows interact with the economy and the environment [20]. The principle of mass balancing is based on the first law of thermodynamics, which states that matter (mass, energy) is neither created nor destroyed by any physical transformation process. Material inputs into a system must therefore always equal material outputs plus net accumulation of materials in the system (material balance principle). Material that flows into the system builds up and maintains the system's material compartments (stocks). Conversely, all materials required to maintain a system compartment or stock must be considered part of the system's relevant material flows.

Material flows can be analysed on several spatial scales and with different instruments depending on the issue of concern and on the objects of interest of the study. The analysis can be applied to the complete collection of resources and products flowing through a system to single chemical elements. MEFA can be applied to various scales and types of systems, e.g. companies, economic sectors, households, national economies, the world economy, or villages, cities, river basins, nation states and world regions [21]. MEFA may include different types of materials. The objects for analysis may range

from specific elements or substances, for example copper [22],[23] or chlorine [24], [25], to all material inputs, including water and air. According to different subjects and various methods, MEFA covers approaches such as Substance Flow Analysis (SFA), product flow accounts, material balancing, and overall material flow accounts [26].

The principle concept underlying the MFA approach is simple model of the interrelationship between the economy and the environment, in which the economy is an embedded subsystem of the environment and – similar to living beings – dependent on the constant throughput of materials and energy [10, 27]. Raw materials, water and air are extracted from the natural systems as inputs, transformed into products and finally re-transferred to the natural systems as outputs (waste and emissions). To highlight the similarity to natural metabolic processes, the terms "industrial"[28] or "societal" [18] metabolism have been introduced.

2.2   MFA definitions

To understand the construction and quantifications of the MEFA approach it is important to recognise the definitions applied. The review uses the definitions from the Practical handbook of Material Flow Analysis by Brunner and Rechberger [9], which are declared in Table 1.

Table 1
Terminology used in MEFA [9]

Term	Definition
Material	Generic term for substances and/or goods flowing through the system
Substance	A chemical element (atom) or compound (molecule)
Good	A material with a positive or negative market value, for example food and waste water
Process	The transformation, transport or storage of material. A process can be natural or man-made
Stock	The storage of material in a process. It is illustrated as a little box within the process box
Flow	An inflow (input) is entering a process and an outflow (output) is exiting a process. Import and export are the flows in and out from the system. The flow is defined as "mass per time" and can for example be measured in g year^{-1}
Flux	The flux is defined as "mass per time and cross section" and can be measured in kg sec^{-1} m^{-2} or g cap^{-1} year^{-1}.
Transfer coefficient	The division of a substance in a process. The percentage of a process's input that is directed to each output
Parameter	The data used for describing the process, i.e. flows, concentration, area and mass
System boundary	The geographic or organizational border of the defined system

2.3   Applications of Material and Energy Flow Analysis

Material and energy flow analysis has become a widely used policy decision support tool in many fields, including process control, resource management, waste treatment, environmental management, product design, and life cycle assessment [9], [29]. Table 2 gives an overview of the studies examined on the application of material flow analysis.

Table 2
Application of Material and Energy Flow Analysis in the reviewed literature

Study criteria	Goods	Substances	References
Substance level		Metals	[30], [31], [32], [33], [34], [35], [36], [37], [38], [12], [24], [25], [22], [23]
		Periodic table elements	[39]
Goods and substance level	Construction materials	Mixture	[40]
	Land trade		[41]
		Metals	[42], [43], [44], [45]
	General	Problematic substances	[46], [47], [48],[49], [50], [15], [51], [52]
Goods	Wood		[17], [53], [54], [55]
	Food products		[56], [57], [58], [59], [60]
	Waste streams		[61], [62], [63], [64], [65], [13], [38], [14], [15]
	Plastics		[66]
	Tailoring		[67]
	Internet, ceramics		[68],[69]

3.0 Materials and methods

3.1 MEFA methodology

The main tool used for this study is the Material and Energy Flow Analysis. It consists of determining and quantifying all flows that are inputs and outputs in a system with the goal of assessing the interchange of resources between the system and the environment. Detailed methodological steps of MEFA are described in [10], [70], [71]. Material and energy flow analysis contains the following main steps [9]: (1) definition of the system under study , (2) system description, (3) data acquisition, (4) modeling and scenario building, and (5) results and discussion.

(1) Definition of the system under study

The first step of MFA is the identification of the industrial plant. It involves the qualitative analysis of the selected process: identification of its limits, definition and description of its stages, and analysis of inputs and outputs and internal flows. This analysis must be based on technical visits to the plant and on bibliographic review.

(2) System description.

The MEFA system under consideration is defined with regard to space (e.g. a city, province, country, or industry), function (e.g. processes), time horizon (e.g. a year) and materials (e.g. the studied substance). If necessary, the system can be divided into subsystems.

(3) *Data acquisition*

The flows and stocks can be determined by direct measurements, market research, expert judgment, best estimates, interviews, databases of environmental protection agencies, scientific papers, technical handbooks and so on.

(4) Modeling and scenario building.

Energy and material balances are performed on those processes where no data is available. The results obtained can be integrated into the model. Computer software of a different degree of complexity are available to support this analysis. The structure of the model for the process considered must be set up carefully to guarantee the quality of the results from the simulation

(5) *Results and discussion.*

The results obtained can be compared with environmental standards and/or sustainable indicators or even other assessment approaches. All of them contribute to design control measures, to identify new problems and best of all, new solutions.

3.2   Material and energy analysis: applications to tea processing

3.2.1   System definition and boundary

This study focussed on the Malawian tea industry, and aims to: (a) analyse the material streams, processes and flows within tea production system; (b) determine and quantify the material and energy consumption for the industry using the MEFA method; and (c) evaluate the environmental inputs and outputs associated with tea manufacture at the factory. The study has a gate-to-gate system boundary and starts at the weighbridge where green leaf from tea fields is received and ends at the production of dried tea at the factory gate. In addition, it includes the energy unit producing electricity (diesel generator), process steam and heat (boilers) as shown in Figure 1. Upstream activities[1] and downstream activities[2] (e.g. distribution and use stage) have not been included in the system. The function unit for this study is 1 kg of made tea in Malawi. Fig.1 also shows the processes and stages included in the system boundary.

3.2.2   System description

Tea processing consists of the following main steps: withering, rolling, oxidation, drying, and sorting and grading. Freshly plucked tea leaves are brought to the factory where they are first withered. Withering is an important processing step applied to reduce the moisture content of the leaf from 75-83% (wet basis) to 68-72% (wet basis) and to prepare the leaf chemically and physically for the subsequent stages of manufacture [72]. In addition, many physical and biochemical changes take place during withering process and results in: an increase in the level of amino acids [73], caffeine content [74], sugars [75], polyphenol oxidase activity [76]; changes in chlorophyll content [77]; formation of precursors of volatile flavour compounds [78]; and an increase in cell membrane permeability [79]. Withering duration ranges from 6 to 20 hours and is a function of relative humidity of the surrounding air, temperature, and the flow velocity of the withering air [80].

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[1] Tea cultivation, production, and transportation to factory
[2] Distribution and usage stage

Withered leaf is cut or macerated using rollers, Lawrie Tea Processor (LTP) or Cut-Tear-Curl (CTC) machines. Rolling bruises the leaves, disrupting the leaf cell structure and brings tea polyphenols and polyphenol oxidase and oxygen in contact, which promotes the oxidation of tea polyphenols and formation of red pigments (thearubigins) and yellow pigments (theaflavins). The macerated leaf or dhool is cooled to temperatures below 35°C to preserve quality. Tea leaves are then subjected to the process of fermentation/oxidation by moving conveyors under controlled temperature, humidity and air flow conditions. Cool air is circulated through the crushed leaves to moderate the reaction, as the onset of fermentation is accompanied by a rise in temperature from the exothermic fermentation process.
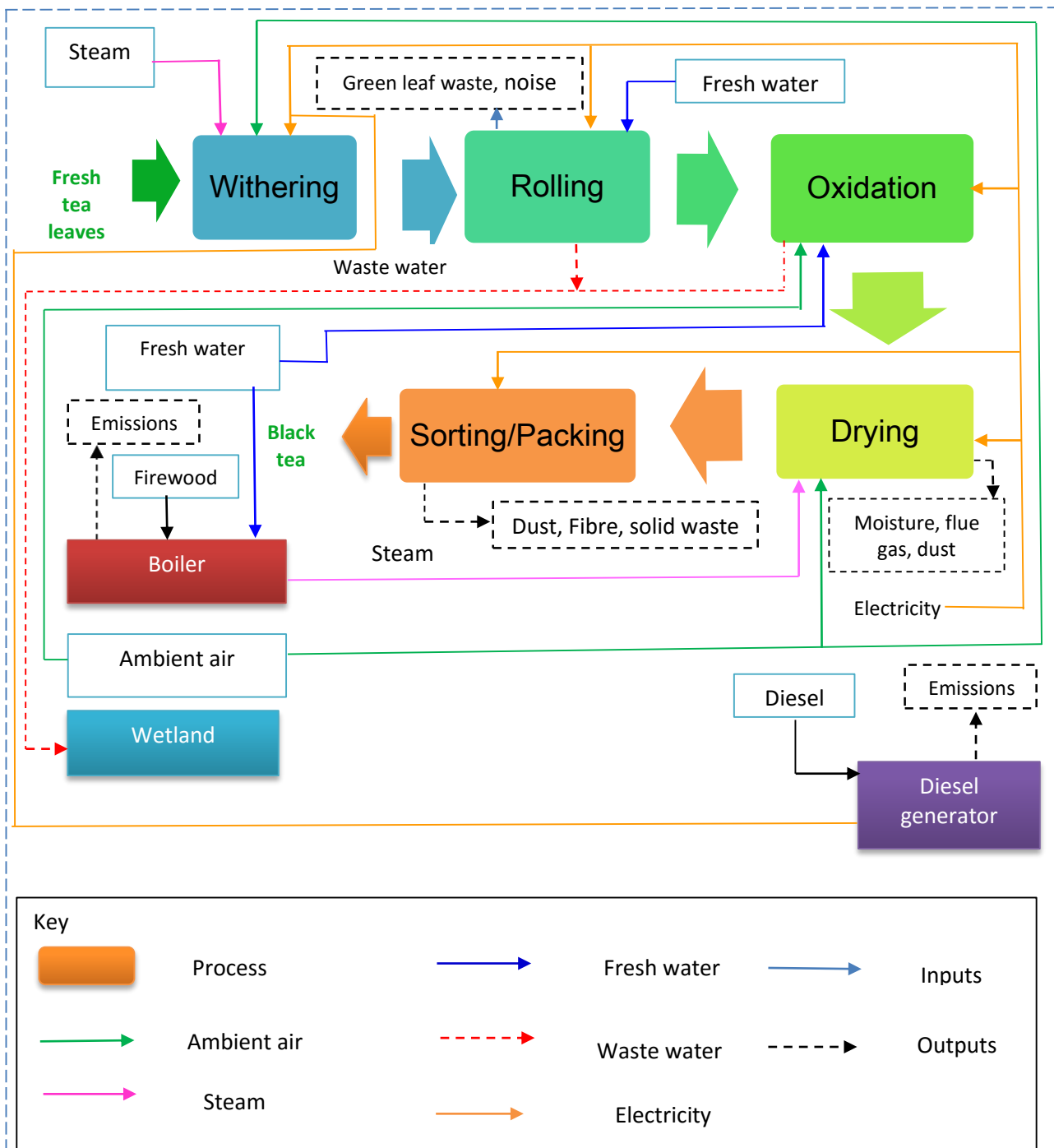

Figure 1: Process flow diagram for tea factory

Humidifiers mounted within the belt fermentation assembly are also used to improve the ability to absorb clean air, and whenever needed. Fermentation/oxidation in tea leaves results in the production of

different chemical compounds, such as "theaflavins (TF)" and "thearubigins (TR)"which respectively contribute to taste, strength and colour of tea. Fermentation/oxidation time depends on the ambient temperature, degree of maceration, degree of wither, and the type of tea to be produced. Typically it ranges from 45 to 60 minutes and 60 to 105 minutes for fast and slow fermenting cultivars, respectively. Temperatures between 20 and 30°C, with high humidity (95%) and ample exposure of the macerated leaf to the air are found to be satisfactory.

The last step of black tea manufacture involves drying with a blast of hot air. Fermented tea leaves are fired to arrest further fermentation, deactivate the enzymes and remove almost all residual moisture in the leaf. The leaf is passed through fluidized bed dryers, which have circuit trays with perforations, on which are conveyed the fermented leaf. The drying process takes about 20 -25 min and the inlet air temperature is about 120 – 140°C and is finished off at a temperature of 80-90°C.The moisture level of the tea when drying is completed is approximately 2-3%. According to Keegel [81], drying is influenced by the inlet temperature, thickness of spread of the dhool, air flow rate, period of drying, and moisture content of the dhool. Dried tea is sorted into different grades by passing it over a series of vibratory screens of different mesh sizes. Stalk is removed by the use of electrostatic separators. The graded tea is finally weighed and packaged into sacks or wooden chests, and subsequently sold at the local and regional auctions. Process steps and the generated wastes from these steps are also given in Fig.1.

3.2.3   Data acquisition

The empirical data of this study was collected from eight of the twenty one tea factories in Malawi. Purposive and convenience sampling techniques [82] were applied to select a sample of factories for this study. The factories have different processing capacities of green leaves ranging from 90 to 240 tons per day. They accounted for approximately 38 percent of total production capacity in the country. Data were collected from these factories through plant reports, direct on-site measurement and literature review. The inventory data which consisted of raw materials, energy consumption, wastes and emissions were collected for a period of seven years from each factory. Data analysis included material and energy inputs and outputs at each stage of tea production. Finally, mass and energy balances for a complete factory and the unit processes were established.

3.2.4   Mathematical modelling

3.2.4.1   Governing equations

Mass balances can be expressed in the rate form as given by the following general equation:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

where $\dot{m}$ is the mass flow rate, and the subscripts *in* stands for inlet and *out* for outlet. Material balances for each step of tea production shown in Fig.1 can be described by Eq. (2):

$$\sum_{j=1}^{p} \dot{m}_{in,j} = \sum_{k=1}^{n} \dot{m}_{out,k} \tag{2}$$

where *j* represents the type of material inputs with a total of *p* inputs, and *k* represents the type of material outputs with a total of *n* outputs.

Energy balance for the considered unit process is given by the following equation:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{3}$$

where $\dot{E}_{in}$ denotes energy rate (kJ)

(1)   Withering

Dry air mass balance: $\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$ (4a)

Water mass balance: $\omega_1 \dot{m}_a = \dot{m}_{a2} \omega_2 + \dot{m}_w \rightarrow \dot{m}_w = \dot{m}_a (\omega_2 - \omega_1)$ (4b)

Energy balance: $\sum \dot{m}_{in} h_{in} = \dot{Q}_{out} + \sum \dot{m}_{out} h_{out} \rightarrow \dot{Q}_{out} = \dot{m}_a (h_1 - h_2) - \dot{m}_w h_w$ (4c)

where $\dot{m}_{a1}$ and $\dot{m}_{a2}$ is mass flow rate of air at the inlet and outlet, respectively; ω_1 and ω_2 represent the humidity ratio of air at the inlet and outlet, respectively; $\dot{m}_w$ is the mass flow rate of water; h_1 and h_2 denote the specific enthalpy at the inlet and outlet, respectively; and $\dot{Q}_{out}$ is the rate of heat transfer.

(2)   Rolling/maceration

Dhool balance: $(\dot{m}_{dh})_1 = (\dot{m}_{dh})_2 = \dot{m}_{dh}$ (5)

where $(\dot{m}_{dh})_1$ and $(\dot{m}_{dh})_2$ is the mass flowrate of dhool.

(3)   Continuous Oxidation/Fermentation

Equations governing mass and energy balance in the continuous fermentation or oxidation process are given as [83]:

Dry air mass balance: $\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$ (6a)

Water mass balance: $\omega_1 \dot{m}_a = \dot{m}_{a2} \omega_2 + \dot{m}_w \rightarrow \dot{m}_w = \dot{m}_a (\omega_2 - \omega_1)$ (6b)

Energy balance: $\sum \dot{m}_{in} h_{in} = \dot{Q}_{out} + \sum \dot{m}_{out} h_{out} \rightarrow \dot{Q}_{out} = \dot{m}_a (h_1 - h_2) - \dot{m}_w h_w$ (6c)

(4)   Drying

Mass balance equations for the dryer shown in Fig 2 can be written considering three components such as fermented or fresh tea leaves, air and the water which exists in the drying air and tea. Mass balance for air, tea and water are given by the equations proposed by Dincer and Sahin [84]:

Air: $(\dot{m}_a)_1 = (\dot{m}_a)_3 = \dot{m}_a$ (7a)

Tea: $(\dot{m}_p)_2 = (\dot{m}_p)_4 = \dot{m}_p$ (7b)

Water: $\omega_1 \dot{m}_a + (\dot{m}_w)_2 = \omega_3 \dot{m}_a + (\dot{m}_w)_4$ (7c)

where $\dot{m}_a$ is mass flow rate of air, $\dot{m}_p$ mass flow rate of tea leaves, ω is the humidity ratio of air, and $\dot{m}_w$ mass flow rate of water.

Energy balance: $\qquad \sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out}$ $\qquad\qquad$ (8)

Consequently, the overall energy balance of the dryer can be written as follows [84]:

$$\dot{m}_a h_1 + \dot{m}_p (h_p)_2 + (\dot{m}_w)_2 (h_w)_2 = \dot{m}_a h_3 + \dot{m}_p (h_p)_4 + (\dot{m}_w)_4 (h_w)_4 + \dot{Q}_l \qquad (9)$$

where $\quad h_1 = (h_a)_1 + \omega_1 (h_v)_1 \simeq (h_a)_1 + \omega_1 (h_g)_2$ $\qquad\qquad$ (10)

$h_3 = (h_a)_3 + \omega_3 (h_g)_3$ $\qquad\qquad$ (11)

where h is specific enthalpy; h_p specific enthalpy of tea; h_g specific enthalpy at saturated vapour state; h_w specific enthalpy of water; h_a specific enthalpy of air, $\dot{m}$ mass flow rate; $\dot{Q}_l$ rate of heat transfer loss; and ω humidity ratio of air.
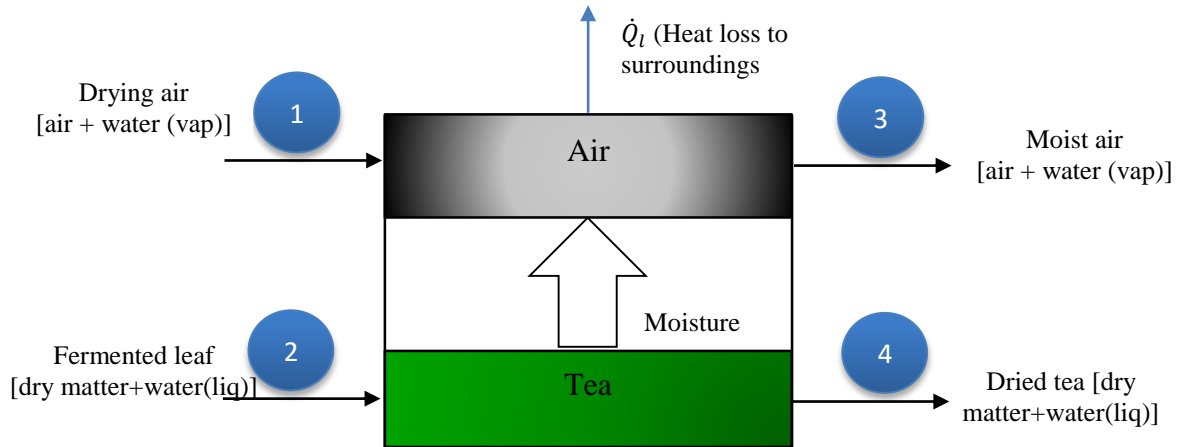

Figure 2: Schematic of drying process with inputs and outputs [28]

Eq. (12) can be used to calculate the heat loss rate from the dryer chamber:

$$\dot{Q}_l = \dot{m}_a q_l \qquad\qquad (12)$$

where $\dot{m}_a$, q_l represent mass flow rate of air and heat transfer related loss, respectively.

(5) Sorting and grading

Dried tea: $\qquad (\dot{m}_{dt})_1 = (\dot{m}_{dt})_2 = \dot{m}_{dt}$ $\qquad\qquad$ (13)

where $\quad (\dot{m}_{dt})_1$ and $(\dot{m}_{dt})_2$ is the mass flowrate of dried tea.

3.2.4.2 Parameters and thermal properties

Enthalpy (heat content) of drying air and the specific heat on inlet and outlet air is determined via Eq.(14) and Eq.(15), respectively.

$$h_a = C_s(T_a - T_0) + \omega h_L \tag{14}$$

$$C_s = 1.005 + 1.88\,\omega \tag{15}$$

where C_s is the humid heat (kJ/dry air); T_a is air temperature (°C), T_0 is reference temperature (°C), ω is the absolute humidity (kg water/kg dry air) of inlet drying air, h_L is the latent heat of vaporization of water (kJ/kg water).

Bhuyan [85] proposes the following equation for calculating the mass of air needed for the drying:

$$m_a = \frac{m_p\left[C_{pp}\left(T_{p1} - T_{p2}\right) + C_{Pw}\left(W_1 T_{p1} - W_2 T_{p2}\right)\right]}{C_{s1}T_{a2} - C_{s2}T_{a1} + h_L(\omega_2 - \omega_1)} \tag{16}$$

where C_{s1}=1.005+1.88ω_1; C_{s2}= 1.005+1.88ω_2; T_{p1} and T_{p2} are inlet and out temperatures of tea, W_1 and W_2 are moisture content of tea at inlet and exhaust; T_{a1} and T_{a2} are the inlet and exhaust temperatures of drying air, respectively, ω is the absolute humidity, and m_p is the feed rate of tea.

The heat content of tea leaves is evaluated from the following equation:

$$h_p = W C_{pw} C_{pp}\left(T_p - T_0\right) \tag{17}$$

where W is the moisture content of the product (kg water/kg of dry solid product), C_{pw} is the specific heat of water (kJ/kg.K), C_{pp} is the specific heat of product (kJ/kg.K), and T_p, T_0 are product and reference temperatures, respectively.

Mass of dried material and the amount of moisture removed from tea leaves are quantified according to Eqs. (18) and (19), respectively.

$$m_{dm} = m_{wm} \cdot \frac{(100 - X_{wm})}{(100 - DM_c)} \tag{18}$$

$$m_{ev} = m_{dr} \cdot \frac{(X_{wm} - X_d)}{(100 - X_{wm})} \tag{19}$$

where m_{dm} is amount of withered leaf , m_{ev} amount of evaporate water; m_{wm} amount of wet material; X_{wm} moisture content of fresh tea leaves; DM_c dry matter content; m_{dr} amount of dried material; and X_d moisture content of withered leaf.

3.4.3   Potential environmental impacts

The potential environmental impacts (PEI) associated with the production of tea are evaluated using the CML 2002 methodology [86]. The method, in compliance with ISO 14040 series, divides a life cycle impact assessment study into classification, characterization, normalization, and weighting. According to Moberg et al., [87], classification is an inventory collection process from life cycle to several impact categories, while characterization entails sorting emissions and resources coming from the inventory into different groups or impact categories according to their potential impact on the environment [88], [89]. The environmental impact categories selected in this study were global warming, acidification, eutrophication, photochemical oxidant formation, and human toxicity. The potential environmental impacts are estimated using the following Eq. (20) and (21) [90]:

$$PEI_i = \sum_{x=1}^{Y} \left(E_{x,i} \cdot CF_{x,i} \right) \tag{20}$$

$$I_j = \sum_{i=1}^{Z} \left(\frac{PEI_i}{N_i} \; x \; V_{i,j} \right) \tag{21}$$

where PEI is the potential environmental impact; E_x total emissions of a substance x; CF_x characterization factor, i potential impact category; N_i normalisation factor; $V_{i,j}$ valuation factor; j represents different sets of valuation factors; and I_j environmental index.

Normalization is the calculation of the magnitude of the category indicator results relative to reference information. The reference information may relate to a given community (for example, in Malawi, Southern Africa or World), person or other system, over a given period of time [91]. Category indicator results are normalized to better understand the relative importance and magnitude of these values for the studied system [92], [93]. Normalization can be determined based on the formula shown as follows [94].

$$N_i = {S_i}/{R_i} \tag{22}$$

where S, R denotes category indicator and reference value, respectively.

Finally, weighting is conducted by multiplying category indicator with weighting factor and summed to get the score [88].

4.0   Results and Discussions

4.1   *Materials and energy inputs*

Table 3 shows the main inputs and outputs for the production of 1 kilogram of made tea. Descriptive statistics for input and output calculations of the analysed factories is also given in Table 4. Inputs to produce black tea include green leaf as the main raw material; energy (electricity, diesel, firewood, water, human labour); and auxiliary materials (chemicals, paper sacks, pallets, straps). The outputs are black tea; wastes including dry waste leaf, boiler ash, tea dust and wastewater; and air emissions. The analysis results show that for the production of 1 kg black tea, a typical Malawian tea factory uses 4.96 kg green leaf (GL), 0.64 kW electricity, 3.35 kg firewood, 9.2 millilitres of diesel, 0.268 hours of human power, 4.24 kg water. The results range from 4.19 to 6.33 kg/kg for green leaf; 0.42 to 1.08 kWh/kg for electricity; 1.67 to 8.2 kg/kg for firewood; 0.14 to 0.51 MJ/kg for diesel; 0.104-0.695 hr./kg for human

power; 1.92 to 8.32 kg/kg for water; and 1.17 to 6.07 g/kg for boiler chemicals. Details of material and energy use are discussed in the following sections.

Table 3
Input and output table for tea production of 1 kg made tea

Parameter	F1	F2	F3	F4	F5	F6	F7	F8
Inputs								
Raw material								
Green leaf (kg)	6.33	4.88	4.19	6.13	4.33	4.68	4.46	4.65
Auxiliary materials								
Paper sacks	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018
Pallets	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009
Energy								
Electricity(kWh)	0.61	1.08	0.47	0.61	0.61	0.73	0.58	0.42
Firewood (kg)	3.13	3.58	1.67	2.42	3.09	2.96	8.2	1.75
Diesel (litres)	0.0087	0.0132	0.0082	0.009	0.0113	0.0036	0.0064	0.0116
Human (hours)	0.195	0.104	0.251	0.695	0.299	0.164	0.621	0.239
Water (kg)	4.53	7.5	1.92	8.32	2.22	3.47	3.26	2.68
Chemicals (g)	0.96	1.17	0.53	1.12	0.23	0.56	0.88	0.62
Outputs								
Black tea	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Waste								
Dry/waste								
leaf (g)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Ash (g)	1.07	1.79	0.78	1.99	0.39	0.8	1.53	0.96
Tea dust (g)	1.2	1.2	1.2	4.94	4.47	1.2	1.2	1.2
Waste water (l)	0.76	2.5	0.55	1.39	0.56	1.39	1.09	0.67
Emissions to the air								
CO_2(kg)	5.41	5.33	2.51	3.66	4.64	4.52	4.72	3.11
CH_4 (g)	35.62	34.99	16.45	24.05	30.45	29.82	31.09	20.36
N_2O (g)	70.13	69.07	32.50	47.45	60.11	58.75	61.29	40.25
NO_X (g)	27.56	27.45	13.07	18.75	23.87	22.76	23.95	16.29
CO(g)	3.54	3.48	1.64	2.39	3.03	2.97	3.09	2.02
NMVOC(g)	0.17	0.17	0.08	0.12	0.15	0.15	0.15	0.10
SO_2 (g)	1.21	1.25	0.61	0.84	1.08	0.96	1.04	0.78
Emissions to water								

Parameter		
COD (mg/l)	n/a	
BOD (mg/l)	335	

Table 4
Descriptive statistics of Malawian life cycle inventory for 1 kg of black tea production

Parameter	Unit	Range	Mean	Std. Deviation (SD)	Coefficient of variation (CV)
Inputs					
Raw Material					
Fresh leaf	kg	4.19-6.33	4.96	0.816	16.5%
Energy					
Electricity	kWh	0.42-1.08	0.64	0.202	32%
Firewood	kg	1.67-8.2	3.35	2.0733	62%
Diesel	MJ	0.14-0.51	0.348	0.119	34%
Human power	hrs	0.104-.695	0.321	0.217	68%
Water	kg	1.92-8.32	4.24	2.414	57%
Chemicals	g	1.17-6.07	0.759	0.326	43%
Output					
Waste					
Dry/waste leaf	g	n/a	0.5	n/a	n/a
Boiler ash	g	0.39-1.99	1.164	0.553	48%
Dust	g	1.2-4.94	2.076	1.627	78%
Wastewater	kg	0.55-2.5	1.11	0.657	59%
Emissions to air					
CO_2	kg	2.51-5.41	4.24	1.045	25%
CH_4	g	16.45-35.63	27.856	6.898	25%
N_2O	g	32.13-70.13	54.94	13.562	25%
NOx	g	13.07-27.56	21.71	5.22	25%
CO	g	1.64-3.54	2.77	0.687	25%
NMVOC	g	0.08-0.17	0.136	0.0338	25%
SO_2	g	0.61-1.3	0.971	0.218	25%

4.1.1 Raw material consumption

Table 1 also presents the results from analysing the amount of green leaf required to manufacture 1 kg of black tea in the studied factories. The results show that the quantity of green leaf to manufacture 1 kg of made tea varies from 4.19 to 6.33 kg green leaf per kg of made tea. The average specific raw material consumption was calculated to be 4.96 kg green leaf per kg of made tea, compared to 4.5 and 4.66 kg green leaf per kg of made in Kenya and Sri Lanka, respectively [95]. Compared to fresh leaf consumption values regarded as the best practice of tea industry in the country, reported in [96], the studied factories consume slightly higher green leaf per kg of made tea. Clearly, this indicates that there is need to improve tea process efficiency of the Malawian tea factories.

4.1.2 Energy consumption

Table 5 presents the results from analysing ranges of specific energy consumption among individual tea factories grouped by country based upon available literatures that were reviewed in this study. The average specific electrical and thermal energy consumption across countries varied significantly, ranging from 0.42 to 1.08 kWh/kg and 5.47 to 14.31 kWh/kg, respectively. The average specific electrical and thermal energy for made tea processed by the Malawian tea industry is found to be 0.64 kWh/ kg and 13.41 KWh/kg of made tea, respectively. Data found in India exhibited a less yet significant spread (i.e. 0.2 – 0.5 and 3.5 - 6 kWh/kg made tea, for electrical and thermal energy, respectively. The results of this study indicate that tea processing in Malawi is relatively energy intensive. The highest energy input is provided by fuel (firewood), followed by electricity and human labour. Usage of diesel is comparatively low in all audited factories, as these use generators during power failure periods only. A smaller amount of diesel is also used to power tractors used with the factory. The average wood consumption in Malawian tea factories is 3. 35 kg/kg made tea compared to 1.38 and 1.372 kg per kg made tea in more efficient factories in Sri Lanka and India, respectively [97],[98].These significant differences have indicated large potential energy saving opportunities in the country's tea factories.

Table 5

Comparison of average annual SEC values in selected countries

Country	Specific electrical energy consumption (kWh/kg)		Specific thermal energy consumption (kWh/kg)		Source
	Average	Range	Average	Range	
Malawi	0.64	0.42 – 1.08	13.41	5.47 – 14.31	
Sri Lanka	0.46	0.69 – 1.47	5.26	4.45 – 6.84	[99],[100]
Kenya		0.44 – 0.56	5.33	4 - 23	[95]
India	0.5	0.2 – 0.5	4.6	4.5 - 6	[101], [100]
Vietnam		0.58 – 0.8	10		[100]

4.1.3 Water Use

Results of water usage in the audited factories are summarised in Table 6. The study shows that tea processing requires smaller, but still considerable, amounts of water. Annual water consumption in the analysed factories varies between 4586 m^3 and 12 120 m^3. More than 38% of the water used in these

factories is used for boiler-feed water[3], followed by domestic use[4] (34%) and factory cleaning (26%). The specific water consumption was found to be low, ranging from 1.92 to 8.32 kg/ kg made tea with average of 4.24 kg/ kg made tea and standard deviation of 2.414 kg/kg of made tea (see Table 2). This figure is comparable with that of India and Sri Lanka, with specific water consumption of 3.584 kg /kg and 8.817 kg/ kg, respectively; and the global average of 7.483 kg/kg made tea [102]. The study also established that most factories do not record water flowing in and out of individual processing units as well analyse these waters.

Table 6:

Water usage at selected tea factories

Factory	Tea Production (kg yr^{-1})	Water input (m^3 kg^{-1} made tea)				Wastewater	
		Total	Boiler	Factory cleaning	Domestic & others	(m^3 kg^{-1})	(kg kg^{-1})
F1	1,311,043	0.00453	0.00181	0.00076	0.00196	0.00453	4.53
F2	1 080 209	0.00750	0.00125	0.00250	0.00375	0.00750	7.50
F3	2 384 549	0.00192	0.00109	0.00055	0.00029	0.00192	1.92
F4	1 128 068	0.00832	0.00277	0.00139	0.00416	0.00832	8.32
F5	5 447 716	0.00222	0.00111	0.00056	0.00056	0.00222	2.22
F6	2 252 108	0.00347	0.00069	0.00139	0.00139	0.00347	3.47
F7	1 437 728	0.00326	0.00174	0.00109	0.00043	0.00326	3.26
F8	2 016 875	0.00268	0.00134	0.00067	0.00067	0.00268	2.68

4.1.4 Waste

Solid waste streams from the analysed factories are composed of dry/waste leaf, dhool spillages, sand and other waste, dust and stalks, tea sweepings, and boiler ash. The analysis indicates that solid waste in these factories account for 0.68% of total production. The highest amount of waste is produced at withering process (0.5%), followed by sorting (0.1%), maceration (0.04%), fermentation (0.02%) and packing (0.02%), respectively. Overall, total solid and liquid wastes per kg of made tea is calculated to be 2.48% which compares well with a figure of 2% given in the literature. According to results of this study, the production of 1 kilogram of made tea results in the generation of 0.0235 kg of dry/waste tea leaves; 1.11 kg of wastewater; 0.0009 kg of sweepings; and 0.0002 kg of packing wastes.

Results further show that a considerable amount of effluent is produced by tea factories. The effluent generated by tea factories originates from the washing of equipment within the factories. The specific wastewater generated range from 0.00055–0.0025 m^3 /kg (0.55 - 2.5 kg/ kg), and is about 1.8% of total tea production. Effluent from tea factory wetlands was found to contain a biological oxygen demand (BOD) of 335 mg/l compared to a national standard of 20 mg/l. This is an indicator that effluent from tea factories has significant impact on this water quality parameter. There were no data on chemical oxygen demand (COD), total dissolved solids (TDS), and total suspended solids (TSS), making it impossible to draw conclusions based on the available data. Despite having little quantitative evidence about the extent of this on the analysed factories, the study identified waste water generation to be a potentially significant cause of environmental impacts for the Malawian tea industry. Further studies are

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[3] Boiler feed water: water introduced into boilers for conversion to steam
[4] Domestic water: water used for drinking, showers, and flushing wastes, etc

required to substantiate this claim. Also, the study also reveals that many tea factories fail to collect data on the environmental implications of their operations.

4.1.5 Emissions

Greenhouse gas (GHGs) emissions and other pollutants to produce 1 kg of tea in the studied factories are provided in Table 2. Tables 7 and 8 show the comparison of GHG and non-CO2 GHG emissions due to fuel combustion by country, based upon available literatures that were reviewed in this study. Results showed that among the three GHGs considered for the estimation the most important contribution is due to carbon dioxide (98%), followed by nitrous oxide (1.3%) and methane (0.7%). Total carbon dioxide emissions vary significantly across countries, ranging from 2.51 to 5.41 kg CO_2 /kg made tea. The average CO_2 emission to produce 1 kg of tea in the sample factories was 4.24 kg, higher than results from other studies [34]. Specific CO_2 emissions in India, Sri Lanka and Vietnam were found to be 2.15; 2.49; and 2.86 kg CO_2 /kg, respectively. Nitrous oxide emissions vary from 32.50 g N_2O kg^{-1} to 70.13 g N_2O /kg, with an average of 54.94 N_2O/ kg of made tea. Average emissions of methane were calculated to be 27.86 g CH_4 /kg of made tea.

Table 7
Comparison of GHG emissions due to fuel combustion in selected countries

	Kg/kg made tea				Source
	CO_2	N_2O	CH_4	CO_2-e	
Malawi	4.24	0.055	0.028	4.32	This study
Kenya				2.27	[95]
India	2.15				[100]
Sri Lanka	2.49			2.7	[100], [95]
Vietnam	2.86				[100]

Total GHG equivalent emissions were calculated to be 4.32 kg of CO_2-eq/kg of made tea as compared to 2.27 and 2.7 kg CO_2-eq /kg in similar factories in Kenya and Sri Lanka, respectively [95]. These results highlight the need to optimize tea production processes in the Malawian tea industry with a view to reduce these emissions. Sulphur dioxide is another pollutant emitted from fuel combustion which is of concern because of its contribution to acid rain. The specific SO_2 emission was found to be 0.97 g SO_2 /kg compared to 0.016 g SO_2 /kg made tea in India. Specific CO emissions is also lowest in Malawian tea factories at 2.77 g CO/kg made tea, compared to 25 g CO/kg in Sri Lanka and 5.6 g CO/ kg in Vietnam. Average non-methane volatile compounds (NMVOC) and nitrous oxide (NOx) emissions were calculated as 0.14 g NMVOC /kg and 21.71 g NOx /kg of made tea.

Table 8
Comparison of non-CO_2 GHG due to fuel combustion in selected countries

	g/kg made tea				Source
	SO_2	CO	NMVOC	NOx	
Malawi	0.97	2.77	0.14	21.71	This study
Kenya					[95]
India	0.016				[100]

| Sri Lanka | 25 | [100], [95] |
| Vietnam | 5.6 | [100] |

4.2 *Mass flows in tea processing*

Figure 3 presents the results of material balances in a typical black tea processing factory in Malawi. Green leaf having 20 - 25% dry matter and 75-80% moisture is withered to 68% moisture and 32% dry matter. Mass balance results show that with a feed of 4.96 kg green tea leaves (20% TS), the following products are obtained: withered leaf (3.36 kg), dry/waste leaf (0.0235 kg). The amount of water evaporated in the withering troughs is 1.60 kg. The amount of air required for withering depends on the ambient conditions, and for 4.96 kg of green tea leaves, approximately 232.5 kg of air may be needed. The average flow rate of air for the withering process is calculated to be 0.0094 m^3/s. There is no change in the mass flow of tea as well as material loss through the rolling process. However, the study provided for 0.5% maximum moisture loss on the fermenting machines, calculated as 0.053 kg. The amount of water used for washing is assumed to be 0.006 kg, but is not process-related. Fermented dhool enters the dryer with moisture content of around 68% and is dehydrated to 97.5±0.5% total solids (TS) and 2.5±0.5% moisture. Thus from 3.307 kg fermented dhool, 1.073 kg (approximately 1 kg) of dried tea is produced. The amount of water evaporated during drying is determined to be 2.233 kg, while the amount of air required for drying is found to be 10176 kg.
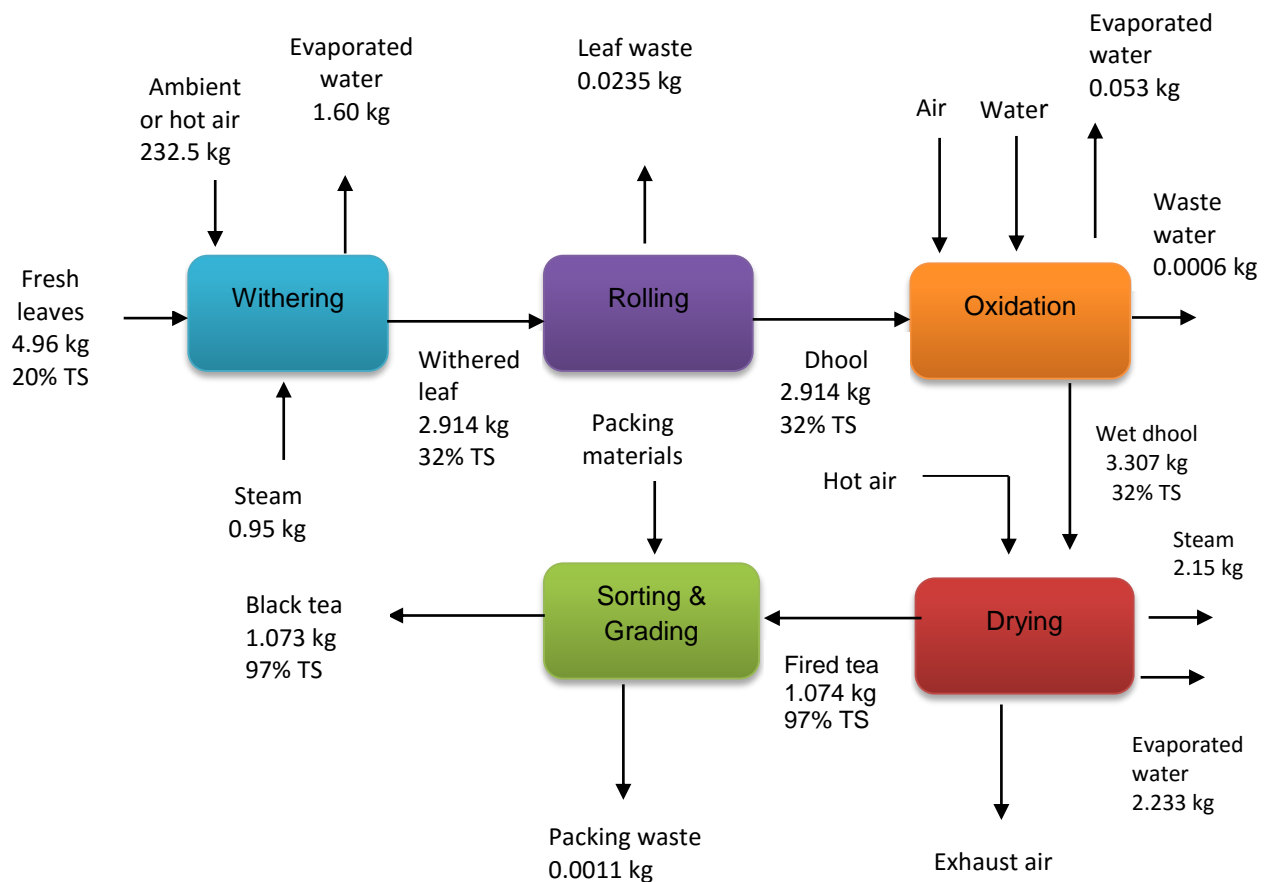

Figure 3: Material balances in black tea processing factory

4.3   Energy flows

Table 9 summarizes and compares the specific energy consumption for unit operations of tea processing across countries. The total energy consumption for tea processing in Malawi is estimated at 8.47 kWh/kg with thermal (85%) and electrical (15%) of the total energy input. Drying consumes the highest energy with 6.37 kWh/kg (78.2%), followed by withering process with 0.83 kWh/kg (16%), while sorting and grading accounted for the least energy with 0.08 kWh/kg (1%). Furthermore, the study found that energy consumption, particularly withering process varied according to climatic conditions, the quantity and quality of plucked tea leaves, and the spreading conditions of green leaf in the troughs. Energy consumption in withering ranges between. Results obtained in this study shows 0that Indian factories consume less amount of withering while Malawian factories consume the highest energy in withering. Specific energy consumption was calculated as 8.47; 7.25, and 5.11 for Malawi, Sri Lanka, and India, respectively.

Table 9

Comparison of energy consumption for unit operations of tea processing in selected countries

	Malawi		Sri Lanka		India		Source
	SEEC	STEC	SEEC	STEC	SEEC	STEC	
				(kWh/kg)			
Withering	0.53	0.83	0.46	2.5	0.1	0.59	[100]
Rolling/CTC	0.31		0.20		0.29		[100]
Fermentation	0.09						
Drying	0.25	6.37	0.07	3.81	0.1	3.86	[100]
Sorting	0.08		0.09		0.16		[100]
Total	1.27	7.2	0.94	6.31	0.65	4.36	
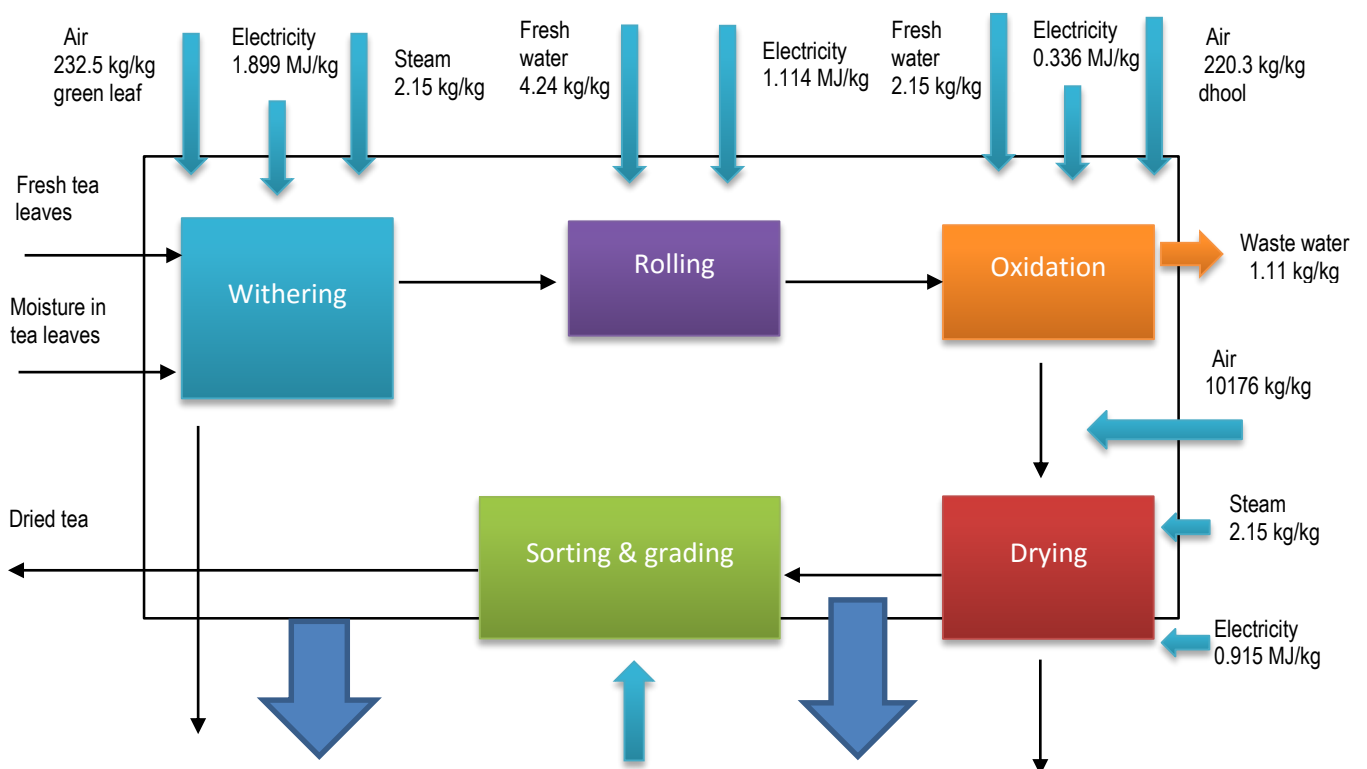
Evaporated water	Exhaust air	Electricity	Exhaust air	Evaporated water
1.60 kg/kg	232.5 kg/kg	0.301 MJ/kg	10176 kg/kg	2.233 kg/kg

Figure 4: Energy flow diagram of tea processing factory

Energy flows in the analysed tea factories are calculated based on energy conservation equations and the results are given in Figures 4 and 5. A psychometric chart is used to determine both the inlet and outlet states of air. Thermal and physical properties of tea were taken from the literature [103]. In this study, the air inlet temperature (before withering) is taken as 26.5°C and relative humidity 70%, resulting in a water content of 0.013 kg water kg^{-1} dry air, according to the enthalpy diagram. The energy balances show the withering process will dehydrate 4.96 kg of green leaf to 3.36 kg of withered leaf (32% TS), removing 1.60 kg of water. The heat energy required for withering 4.96 kg of tea leaves was determined to be 2900 kJ. The corresponding energy per kg of water, as 2900 kJ is required to remove 1 kg of water was calculated to be 1450 kJ. The amount of air entering the trough is estimated to be 232.5 kg. Firewood used in the withering process for dehydration of water is 0.21 kg kg^{-1} of water removed. The amount of steam used for removal of water is determined to be 0.95 kg steam per kg of water evaporated.

Fuel
Mass (kg): 1.00
GCV(kJ/kg): 19 346

$Q_o = 3457$ kW

Combustion chamber

Combustion air
Mass (kg): 16.34
RH (%) : 60
Temp (°C): 31
Moisture (kg/kg):0.0204

Steam
Mass (kg/s) : 1.389
Temp (°C) : 185
Enthalpy (kJ/kg): 2782

$Q_i = 4738. 5$kW

Hot air
Mass (kg): 1.00
Temp (°C): 140
Moisture (%) 3
Moisture (kg) 0.03

$\dot{Q}_l$ (Heat loss to surroundings

Fresh air
Mass (kg) : 232.5
RH (%) : 60
Temp (°C): 29
Moisture(kg/kg):0.015

Radiator

Air

Exhaust air
Mass (kg): 232.5
RH (%) : 34
Temp (°C): 80
Moisture (kg/kg):0.015

Moisture

Fermented dhool
Mass (kg): 1.00
Temp (°C): 80
Moisture (%) 68
Moisture (kg) 0.03

Tea

Dried tea
Mass (kg): 1.00
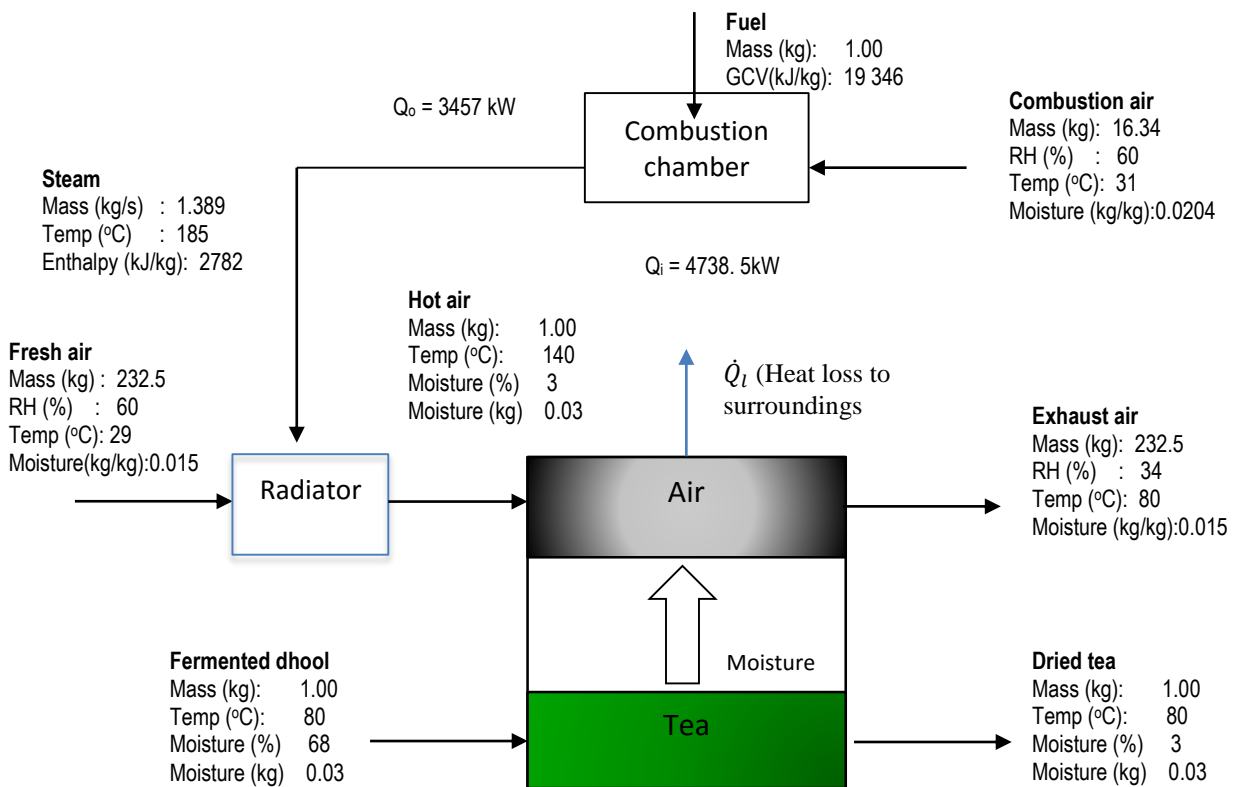Temp (°C): 80
Moisture (%) 3
Moisture (kg) 0.03

Figure 5: Energy calculations for drying tea leaves

Total air mass flow rate is 32.2 kg/s and the product mass flow rate is then calculated to be 0.167 kg s^{-1}. The fluidized bed dryer will dehydrate 2.233 kg of fermented dhool to 1.07 kg of made tea (97% TS), removing 1.97 kg of water. The heat energy required for drying 2.233 kg of fermented dhool was determined to be 3809 kJ. The corresponding energy per kg of water removed was calculated to be 1450 kJ. The amount of firewood used in fluidized bed drying for removal of water is 0.21 kg firewood per kg of water removed. The amount of steam used for removal of water is determined to be 2.15 kg steam per kg of water evaporated, while the unit energy input rate to the dryer is calculated to be 3718 kJ/h.

The main heat source in the process is firewood and the input heat rate is 6003 kJ/h. The evaporation rate in the fluidized bed dryer was 0.027kg water per kg leaf per hour.

4.4 *Environmental impacts*

The life cycle impact assessment (LCIA) method used for this study is the CML 2002, which defines an environmental profile by quantifying the environmental effect of various processes analysed [104]. Table 10 presents the potential impacts, normalisation, and normalised potential impact results for the production of 1 kg of made tea in Malawi. Normalized results for a typical tea processing factory is shown in Figure 6. There are five impact categories for this life cycle impact assessment applied in this study: acidification, eutrophication, global warming, photo-oxidant formation, and human toxicity. The analysis clearly shows that the highest environmental impact is global warming (88%) followed by acidification (6%) and eutrophication (2%), whereas that of human toxicity is lowest. Boiler fuel combustion and diesel for stand-by power generation were the main fuels that contribute to these environmental impacts.

Table 10

Potential impacts, normalisation and resulting normalised potential impacts for impact   categories

Impact category	Potential impact (PI_i)	Normalisation factors (N_i)	Normalised potential impact (PI_i/N_i)
Acidification Potential (AP) in kg SO_2-eq.	0.01205	2.34 E+11	5.01 E-13
Eutrophication Potential (EP) in kgPO_4^{3-}eq.	0.002822	1.77 E+11	5.14 E-14
Global Warming Potential (GWP 100 years) in kg CO_2-eq.	21.14	4.22 E+13	1.59 E-14
Human toxicity Potential (HTP) in kg DCB-eq.	0.026236	7.19 E+11	1.2 E-14
Photochemical Oxidant Formation Potential (POCP) in kg C_2H_4-eq.	0.000546	4.55 E+10	3.65 E-14

DCB: 1.4-dichlorobenzene

Results of this study also indicate that nitrous oxide and nitrogen oxides are the main contributors, with 16.26 kg CO_2 eq/kg of and 0.0109 kg CO_2 eq/kg of made tea, for global warming and acidification, respectively. The total impact associated with global warming and acidification is calculated as 21.14 kg CO_2 eq/kg and 0.012 kg CO_2 eq/kg of made tea, respectively. These results provide a first impression of the contribution of the Malawian tea industry towards these five environmental impacts.
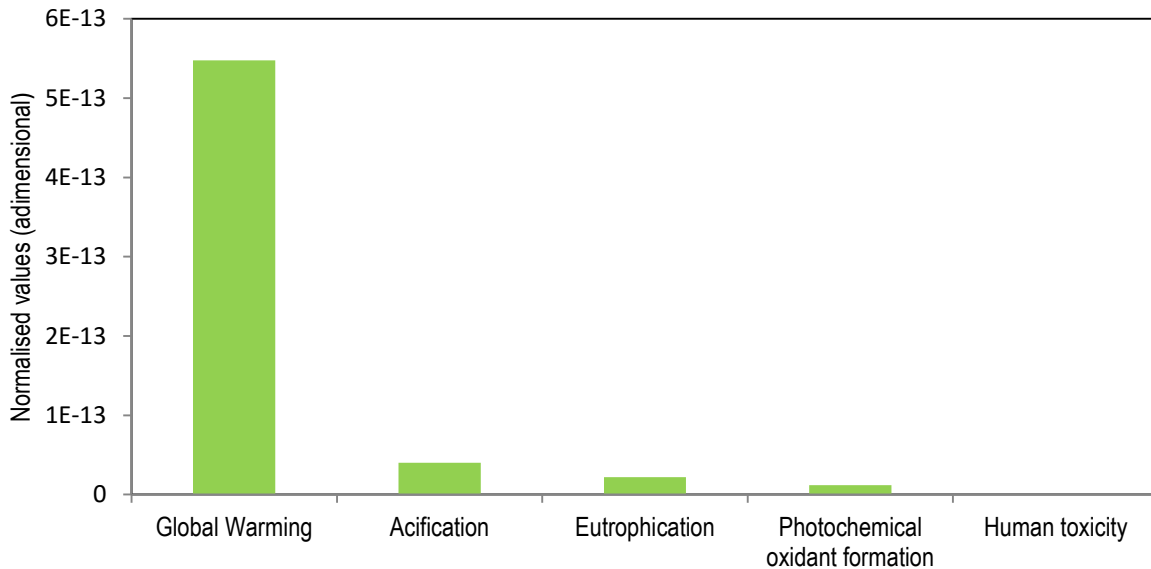
Figure 6: Normalised results for tea production using CML 2000 methodology

5.0   Conclusions

This paper has reviewed the relevant literature on material and energy flow analysis, discussed the concept, methodology and its applicability to the tea industry. The review has also presented analysis results of material and energy flows that take part in black tea manufacture in Malawi. The essence of this study is to identify improvement opportunities in the tea manufacturing process and reduce their environmental impacts while maximising economic, social and environmental benefits. The results obtained are of significance to tea factories as they can be used to modify the operating conditions of factories in terms of material usage, amounts of electricity and firewood consumed, water usage, wastewater generation and emissions. The study discussed in the paper leads to the following major findings and conclusions:

The overall energy and material inputs in tea factories in Malawi is higher compared with factories in Kenya, India and Sri Lanka. The study reveals that 4.96 kg green leaf, 0.64 kWh electricity, 3 .55 kg firewood, 9.2 ml diesel, 0.268 hours of human power, and 4.24 kg water are used to manufacture 1 kg of black tea. The specific raw material consumption varies significantly from 4.19 to 6.33 kg green leaf per kg of made tea, with an average of 4.69 kg green leaf per kg made tea, compared to 4.5 and 4.66 kg green leaf per kg of made tea for factories in Kenya and Sri Lanka, respectively. The average wood consumption in these factories is 3.35 kg of firewood per kg of made tea compared to 1.38 and 1.372 kg of wood per kg of made tea in more efficient factories in Sri Lanka and India, respectively; while the specific water consumption varies from 1.92 to 8.32 kg of water per kg made tea, with the mean of 4.24 kg of water per kg of dried tea, clearly indicating a huge consumption per kg of made tea.

   Energy consumption per 1 kg of made tea varied significantly in tea factories under study, resulting in similar differences in emissions. Significant amounts of GHG emissions associated with tea processing at factory level were found from the combustion of boiler fuel and diesel for stand-by power generation. The study found that 4.24 kg CO_2, 54.94g N_2O, 27.86 g CH_4, 0.97g SO_2, 2.77 g CO, 0.14 g NMVOC, and 27.71 g NOx are emitted to the air per kg of black tea produced. GHG emissions from tea production are estimated to be 4.32 kg of CO_2-eq/kg made tea compared to 2.27 kg CO_2-eq/kg in similar factories in Kenya. Analysis results show that the highest environmental impact is global warming (88 percent) followed by acidification (6 percent) and eutrophication (2percent), whereas that of human toxicity is lowest. These results highlight the need to optimize tea production processes with a view to reduce these emissions.

The results of this study further reveal that withering process requires 2900 kJ of energy to remove 1.6 kg water, using 232.5 kg of air and 0.95 kg steam. The specific energy use in the withering process is calculated to be 1450 kJ per kg made tea. The study also found that drying is by far the most energy-consuming operation within the tea industry. However, the heat energy required per kg of water evaporated is higher than that energy required in withering troughs. The specific energy use in fluidized bed drying was determined to be 1776.6 kJ/ kg water evaporated. The amount of firewood and steam used were 0.21 kg and 2.15 kg, respectively.

The findings demonstrate how MEFA provides early recognition of environmental problems and how it can be used to establish priorities for operating changes over existing factories. These results highlight a very small portion of the life cycle of black tea production since it considered the processing stage only. Further work is required to substantiate the claims made in this study; to initiate continuous resource efficiency analysis in the Malawian tea industry; and to extend the system boundary to include tea cultivation, production and transportation to factory.

Acknowledgements

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