Modelling Energy and Environmental Impacts of Traditional and Improved Shea Butter Production in West Africa for Food Security

Colleen C. Naughton^{a}, Qiong Zhang^b, and James R. Mihelcic^c*

^{a*}**Corresponding Author**

Colleen C. Naughton, PhD

Civil & Environmental Engineering

University of South Florida

4202 E. Fowler Avenue, ENB 118

Phone: (813) 974-2275; Fax: (813) 974-2957; E-mail: cnaughto@mail.usf.edu

^b Qiong Zhang, PhD

Civil & Environmental Engineering

University of South Florida

4202 E. Fowler Avenue, ENB 118

Tampa, FL 33620-5350

Phone : (813) 974-6448 ; Fax : (813) 974-2957 ; E-mail : qiongzhang@usf.edu

^c James R. Mihelcic, PhD

Civil & Environmental Engineering

University of South Florida

4202 E. Fowler Avenue, ENB 118

Tampa, FL 33620-5350

Phone : (813) 974-9896 ; Fax : (813) 974-2957 ; E-mail : jm41@usf.edu

ABSTRACT

This study improves the global application of methods and analyses, especially Life Cycle Assessment (LCA), that properly incorporates environmental impacts of firewood and a social sustainability indicator (human energy) as tools for sustainable human development. Specifically shea butter production processes, common throughout sub-Saharan Africa and crucial to food security, environmental sustainability, and women's empowerment, are analyzed. Many economic activities in the world rely on firewood for energy and labor that aren't included in traditional LCAs. Human energy (entirely from women) contributed 25-100% of shea butter production processes (2,000-6,100 KJ/kg of shea butter) and mechanized production processes had reduced human energy without considerably greater total energy. Firewood accounted for 94-100% of total embodied energy (103 and 172 MJ/kg of shea butter for improved and traditional shea butter production processes respectively) and global warming potential and 18-100% of human toxicity of the production processes. Implementation of improved cookstoves modeled in this study could reduce: (1) global warming potential by 78% (from 18 to 4.1 kg CO₂ eq/kg and 11 to 2.4 kg CO₂ eq/kg of shea butter for the traditional and improved processes respectively), (2) the embodied energy of using firewood by 52% (from 170 to 82 MJ/kg and 103 to 49 MJ/kg for the traditional and improved processes respectively), and (3) human toxicity by 83% for the non-mechanized traditional and improved processes (from 0.041 to 0.0071 1,4 DB eq/kg and 0.025 to 0.0042 1,4 DB eq/kg respectively). In addition, this is the first study to compare Economic Input-Output Life Cycle Assessment (LCA) (EIO)-LCA and process-based LCA in a developing country and evaluate five traditional and improved shea butter production processes over different impact categories. Overall, this study developed a framework to evaluate

and improve processes for achievement of the United Nation's Sustainable Development Goals for 2030 particularly to obtain food security.

Key words: Human energy, sustainable development, food security, gender, world oil crops, sub-Saharan Africa, Life Cycle Assessment (LCA)

1. Introduction

The second goal of the Sustainable Development Goals (SDGs) is to eradicate hunger, obtain food security and proper nutrition, and foster sustainable agriculture (UN, 2015). Unfortunately, one in nine people in the world are undernourished (UN, 2015) and the highest percentage reside in sub-Saharan Africa (WFP, 2015). Furthermore, agriculture is the most common form of livelihood worldwide and is also one of the largest contributors to anthropogenic greenhouse gas emissions (Soussana, 2014; WFP, 2015). Assessing the sustainability of current and future improved agricultural processes requires a framework that properly evaluates the environmental impacts and the contribution of human energy (a measure of social sustainability). Human energy is a critical component to incorporate because a decrease in environmental impact may place an increase of human energy on others, particularly farmers and poorer populations. Expending excessive human energy without adequate compensation and nutrition is a human health concern (Loake, 2001) and can lead to malnutrition and exhaustion and consequently a compromised immune system and sickness (Kau et al., 2011).

Life Cycle Assessment (LCA) is a tool that quantifies the environmental impacts of a product or process from extraction of resources through end-of-life disposal. It is seeing increased use in developing world settings (e.g. Cornejo et al., 2013; Musaaazi et al., 2015) but there are limited applications reported for food security (Efole Ewouken et al., 2012). LCA has

however been recognized as crucial to achieving sustainable food systems, one reason being Western diets incorporate ingredients that may originate from many countries (Soussana, 2014). LCA has been utilized to quantify and compare the environmental impacts of oil crops (e.g. Mattsson, 2000; Achten et al., 2010; Schmidt, 2015); however, most of these studies exclude the human energy involved and focus on limited impacts. Giampietro et al. (1992) did employ energy analysis to compare cattle systems that included human labor but this has not been conducted for edible oil crops. Oil crops such as oil-palm, soybean, cocoa and shea butter have a high food energy content and are crucial to food security as well as economic livelihoods (Ntiamoah and Afrane, 2008). Also, the oil crop sector has been growing twice as fast as the rest of the global agriculture sector and oil crops are estimated to contribute 45 of every future 100 kilocalories added to food consumption in developing countries (FAO, 2002).

Shea trees (*sp. Vitellaria paradoxa*) cover a 3.4 million km² area across 23 sub-Saharan African countries (Naughton et al., 2015) that bear fruit encasing a nut and kernel from which shea butter can be extracted after processing. In fact, shea butter contributes up to 60% of fat and oil supplies in some countries (Tano-Debrah, 1995) with large international exports and considerable potential as a cocoa butter equivalent. Shea fruit is hand-picked from the ground below trees, then the fruit pulp is removed and the remaining shea nuts are boiled or roasted. The shea nut is then dehusked, leaving the kernel that is then ground into a paste to which water is added and mixed vigorously to extract the fat. Shea butter is also unique because the process is primarily controlled by an estimated 18 million women (Naughton et al., 2015) and profits supplement household expenditures (Pouliot, 2012). Furthermore, shea butter may be a more environmentally friendly oil because it doesn't require intensive changes in land use and fertilizer inputs like palm and soy (Glew and Lovett, 2014). However, the production process is

labor and energy intensive and utilizes firewood that contributes to deforestation and negative health impacts (Glew and Lovett, 2014; Jasaw et al., 2015).

Although a carbon footprint analysis was conducted on the improved shea butter production process for cosmetic use (Glew and Lovett, 2014), to date, there is no other LCA of shea butter production including variations of the process, human energy, and environmental impact categories than carbon dioxide. Moreover, shea butter provides an example of a production process undergoing change from traditional to improved methods with mechanization in developing countries and these changes need to be modeled to quantify their environmental and social impacts (Giampietro and Pimentel, 1992). Therefore, the primary aim of this study is to assess the differences in traditional and improved shea butter production and how technological improvements impact the environment and amount of human energy expended to identify areas of improvement for sustainable oil crop production. A combination of field measurements, energy analyses, and different life cycle inventory methods (Economic Input-Output (EIO) and process-based) and sensitivity analyses are utilized and compared in this study.

2. Materials and Methods

LCA entails four major steps: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment, and (4) interpretation (ISO, 2006). Two approaches have been used in life cycle inventory analysis: process-based (bottom-up) and Economic Input Output (EIO) (top-down). Additionally, several studies have also conducted human energy analysis throughout processes that were often excluded in LCA (Loake, 2001; Grimsby et al., 2012; Held et al., 2013). This study employed, compared, and evaluated the process-based LCA, EIO-LCA, as well as a human energy analysis of five shea butter production processes that

incorporated embodied energy and emissions from firewood and a four-part sensitivity analysis from in-depth data collection in the field and literature.

2.1 Shea Butter Production Processes

There are nine major steps in West African shea butter production (see Figure 1): (1) harvest the shea fruit, (2) depulp the fruit, (3) heat the shea nuts, (4) dry the shea nuts, (5) de-husk the nuts to extract the kernels, (6) macerate the kernels, (7) mill the macerated kernels, (8) extract the oil from the kernels, and (9) refine the oil. For the rest of this manuscript the specific production step referred to is provided in parentheses. Traditionally, shea butter production is performed manually though there is increasing access to technology for mechanization of three steps: macerating (6), milling (7), and extraction (8). Furthermore, there are variations of production steps throughout West Africa. For example, in much of Mali the shea nuts are heated (3) and dried (4) using traditional roasters while in other parts of Mali and throughout Burkina Faso and Ghana, shea nuts are heated (3) by boiling over a three-stone fire and then sun dried (4). There has been an effort by non-government organizations and industry to promote the “improved” shea butter process of boiling and sun drying because it is believed to yield higher quality butter, use less firewood, and have a higher extraction rate. Thus, as part of the study aim, five different shea butter production processes were analyzed:

- A. *Traditional process*: Completely manual where traditional roasters are used to heat (3) and dry (4) the shea nuts.
- B. *Mechanized traditional process*: The traditional process A with substitution of mechanized maceration (6) and milling (7).
- C. *Improved process*: Completely manual with substitutions of boiling for heating (3) and sun drying (4).

D. *Mechanized improved process*: The improved process C with addition of mechanized maceration (6) and milling (7).

E. *Further mechanized improved process*: The improved process D with further addition of mechanized extraction (8).

Figure 1. Nine steps and system boundary for the shea butter production process (dashed lines indicate potential inputs based on process variations) (adapted from Adams, 2015).

Waste products such as the uneaten fruit pulp, shea nut husks, and shea wastewater were not included in the system boundary because they were the same for all processes and their environmental impacts were assumed negligible because they were composted locally. Maceration, milling and extraction machines and their transportation from the port of manufacture (Kandla, India) to Dakar (Senegal) (Ports.com, 2015) was also included in the system boundary. The overland transportation between Dakar and Mali was assumed negligible in comparison to the shipping distance (Held et al., 2013). Additionally, products manufactured locally from recycled materials (e.g. large metal cauldrons to boil nuts, large wooden mortar and pestles to macerate the kernels manually) were not included in the system boundary because they were primarily used for cooking purposes and were the same for all processes.

2.2 Study Site and Shea Weighing

Data collection for this study took place in the rural village of Zeala (669 people) in Mali, West Africa approximately 90 kilometers Northwest of the capital, Bamako from 2009-2014, where the lead author lived and served in the Peace Corps as part of a Master's International Program (Mihelcic et al., 2006; Manser et al., 2015). Mali is a representative example of shea butter production with the second largest shea butter production potential in West Africa (Naughton et al., 2015) and where both the traditional and improved process variations are practiced. For LCI and human energy calculations, data from weighing shea fruit, nuts, kernels, butter and firewood throughout the production process were utilized. A local (100 kg +/- 0.5 kg) metal scale and a luggage scale (22 kg +/- 0.25 kg) were used throughout three shea seasons (2012-2014). In 2012, all women collectors in Zeala (N = 120) participated in the study and the total shea butter production of the village was determined by a combination of weighing and calculating the shea butter produced using average extraction rates from shea fruit, nuts, or kernels that were weighed in the village. In 2013, data collection focused on firewood usage and the sample size was reduced to 35 representative women producers. In 2014, shea and firewood were weighed for 25 representative women collectors because the study focus was expanded to include ethnographic surveys (surveys not included in this study). From this data, extraction rates and firewood usage throughout the production processes were averaged (Tables A.1 and A.2). Shea fruit, nuts, kernels and butter weighed throughout the process that fell outside of two standard deviations of the mean extraction rates (95% confidence interval) were removed as outliers.

In 2012, women in Zeala collected approximately 44 tons of shea fruit and produced 3.3 tons of butter. 23 tons of shea fruit (51%) and 1.6 tons of butter (48%) were weighed and the

remaining was determined based on average extraction rates when shea in one stage (i.e. one or a combination of fruit, nuts, or kernels) were weighed due to time limitations of the women and data collectors. The average producer collected 370 kg of shea fruit and produced 28 kg of shea butter. The women collectors reported that 2012 represented an average production year as the shea trees go through cycles of low and high productivity.

2.3 Human Energy Analysis

Additional data collection for the human energy analysis of shea butter production included participant observation of the production processes during the 2009-2014 shea seasons and recording of the duration of each of the nine production steps (Figure 1) using a stop watch (+/- 1 second). Given the type of activity, a physical activity ratio (PAR) can be assigned. PAR is the energy required for a specific task based on a multiple of a person's basal metabolic rate (BMR) (FAO, 2001). Human energy was then calculated using the PAR, the average BMR of a 70 kg active male and duration of the activity (Held et al., 2013). The BMR for a 70 kg male was deemed appropriate as an average between the lower BMR of an average female and the higher BMR of a pregnant or nursing women (most of the collectors) (Held et al., 2013). For example, to calculate the human energy for shea harvesting (1), the total collection time was recorded, a GPS unit was used to collect the coordinates of the trees where fruit was collected, and the shea fruit was weighed at the end of collection. The GPS coordinates for each collection trip were imported into a Geographic Information Systems software, ArcMap 10.1, and overlaid onto a WorldView-2 high resolution (2 meter) satellite image of the study location. The ruler tool was used to calculate the distance traveled by collectors. Average walking speeds, 4.8 km/hr to the collection site and 3.2 km/hr carrying shea fruit on heads (Held et al., 2013; Adams, 2015), were used to calculate the amount of time spent for each stage of shea harvesting as each stage had

different levels of physical intensity (i.e. walking to the collection site is less taxing than walking with an average load of 24 kg of shea fruit (N = 14)). Women collectors in Zeala walked an average of 5.3 km (N = 13) to collect shea fruit. Table A.3 provides a description, sample size, and the human energy data collection methods for each stage of the shea butter production process. Also, Tables A.4-A.8 include the PARs, duration, steps, and human energy expended for each of the shea butter production processes.

2.4 Economic Input-Output LCA

The goal of the EIO-LCA was to quantify and compare the embodied energy of the five different shea butter production processes to identify areas for process improvement. The functional unit was 1 kg of shea butter using the system boundary in Figure 1. The LCI of an EIO-LCA requires the prices of goods and services throughout the process. Two shea butter cooperatives in Mali and hardware stores in Bamako were consulted for prices of macerating and milling machines, housing materials for machinery, and machine installation and repair. Shipping prices of the machines was obtained from the ADICO International manufacturer. Embodied energy values were calculated from an online tool (CMU, 2015) using China 2002 (122 sectors) for imported items (i.e. milling machine, diesel engine, housing materials) and an input-output matrix of the Malian economy from 2006 (17 sectors) for machine construction, installation, and repair (Held et al., 2013). Furthermore, the embodied energy of firewood was incorporated into the EIO-LCA by multiplying the Net Caloric Value (NCV) of firewood from IPCC guidelines (IPCC, 2006) by the mass of firewood measured in the field. Tables A.9-A.13 provide the full EIO LCI data.

2.5 Process-based LCA

The goal of the process-based LCA was to quantify and compare the environmental impacts of four different shea butter production processes (A-D) and identify areas for improvement. Shea butter production process E was not included in the process-based LCA because relative weights and materials of the shea butter extraction machine were not obtainable. The functional unit was 1 kg of shea butter using the system boundary in Figure 1. For the process-based LCI, the Ecoinvent database in the SimaPro 7.2 software (PréConsultants, 2008) was used. ADICO International manufacturer (Gujarat, India) provided relative weights and types of materials of the milling machine and diesel engine utilized for the mechanized maceration (6) and milling (7) steps. Materials and relative weights for the housing of the machines were obtained from visits to four facilities in Mali as well as hardware stores in the capital, Bamako. Material and transportation inputs were divided by the average amount of shea butter produced in Zeala in 2012 multiplied by ten years (average life span of machines and housing) for standardization to the functional unit (1 kg of shea butter). The diesel engine was observed to require an 8-liter oil change 3 times a year and diesel fuel consumption was measured to be 0.0304 L/kg of shea butter (Adams, 2015). The Ecoinvent database does not include firewood emissions associated with a three-stone fire. Thus, emission values for carbon dioxide, carbon monoxide, and particulate matter < 2.5 μ m (PM_{2.5}) for a three-stone fire based on laboratory tests (Jetter et al., 2009) were entered separately. Table A.14 provides the full process-based LCI.

For the impact assessment of the process-based LCA, three impact indicators from the CML 2001 database through the SimaPro 7.2 software were selected as most relevant to shea butter production: Abiotic Depletion (a measure of the extraction of fossil and mineral resources), Global Warming Potential, and Human Toxicity (fate, exposure, and effects of toxic

materials on human health) (PréConsultants, 2008). For each impact category, process inputs are converted into an equivalent (eq) amount of the reference chemical (CO₂-eq for Global Warming Potential, kg antimony or Sb-eq for Abiotic Depletion, and 1,4-dichlorobenzene or 1,4 DB-eq for human toxicity) based on characterization factors or models (PréConsultants, 2008; CML, 2006). In a review of 23 LCAs for selection of an impact category for timber products in Ghana, CML 2001 was widely used and internationally recognized (Eshun et al., 2011) and was thus employed in this study. Embodied energy was also calculated using the Cumulative Energy Demand 1.07 database in SimaPro 7.2 for comparison with the EIO-LCI.

. 2.6 Sensitivity Analysis

A four-part sensitivity analysis was conducted to account for variation in shea butter production and estimate potential reductions in human and embodied energy and environmental impacts from different improvements and scenarios. First, researchers in other studies in Ghana have weighed firewood, calculated extraction rates, and collected time data for the improved shea butter production process (Ojeda, 2009; Jibreel, 2013; Adams, 2015; Jasaw et al., 2015). A lower and upper range of these values were determined to better represent the variation in shea butter production throughout West Africa. Next, the reductions of human and embodied energy, human toxicity, and global warming potential from improved cookstoves were estimated based on emission and firewood reductions from laboratory analyses (Jetter et al., 2009). Moreover, field emissions have been measured at almost twice those of laboratory analyses (Roden et al., 2009) and this was accounted for in the sensitivity analysis of the process-based LCA. Finally, a scenario was modeled in the process-based LCA where the traditional roaster was assumed to have emissions similar to the WFP's improved rocket cookstove (Jetter et al., 2009). Emission

factors of traditional roasters in Mali have not yet been conducted and they may have lower emissions because of their larger combustion chamber.

3. Results and Discussion

The results of three different methods (human energy analysis, EIO and process-based LCA) are presented and compared to thoroughly evaluate the different shea butter production processes. The different outputs from these methods will provide insight and emphases on the various production processes and their stages that may otherwise be missed with only one method. Furthermore, incorporation of human and biomass (firewood) energy are important in the current developing country, human labor intensive and low mechanization context of shea butter production.

3.1 Human Energy Analysis

Overall, the traditional shea butter production process (referred to as A in the figure) requires the highest amount of human energy (6,100 KJ/kg of shea butter), followed by the improved process (C) (5,900 KJ/kg), the improved-mechanized (D) (2,600 KJ/kg), traditional-mechanized (B) (2,500 KJ/kg), and further improved-mechanized (E) (2,000 KJ/kg) processes (see Tables A.4-A.8). Although the traditional processes (A and B) used 40% more firewood (average 11 kg/kg) than the improved processes (C-E) (average 6.6 kg/kg) which requires more human energy for firewood collection, there is not a large difference between the total human energy required between the two processes, particularly when considering the range of human time spent and firewood used for each of the nine production steps reported in the literature. For example, the improved processes (C-E) involve more human energy to collect water and to take shea nuts in and out to sun dry when it rains than to roast the nuts in the traditional processes (A

and B) (see Figure A.1 for human energy comparison of the different production processes in KJ/kg). Furthermore, the improved-mechanized process (D) requires more human energy than the traditional-mechanized process (B) because the improved-mechanized process entails manual crushing and roasting of kernels before mechanized maceration and milling while the kernels in the traditional process can be fed directly into the machine.

Figure 2. Human energy of each step of the shea butter production process as a percent of total human energy for each process variation. Sensitivity bars represent the range of energy values from other human time values reported in the literature (Jibreel et al., 2013; Adams, 2015; Jasaw et al., 2015).

In Figure 2, the human energy required for all nine production steps is shown as a percent of the total human energy of the five production processes (A-E) to display the relative importance of each step for the various processes. For example, in the two non-mechanized processes (A and C), the maceration and milling steps have the largest human energy followed by harvesting of the shea fruit, extraction, and firewood collection. However, with mechanized

maceration and milling, shea fruit harvesting becomes the most energy intensive production step even when accounting for the ten kilometer, round-trip travel women take to a local milling facility (Adams, 2015). Further mechanizing the process for shea butter extraction (E) can reduce the third largest human energy intensive step from 605 KJ/kg of shea butter to only 13 KJ/kg. Reducing human energy of shea butter production is particularly important because it may allow women to allocate more time and energy to hygiene, food security, and income generating activities (FAO, 2015) including collecting more shea fruit (Adams, 2015).

3.2 Energy Comparisons

The EIO-LCA results (including embodied energy from firewood) from Tables A.9-A.13 demonstrate that the traditional-mechanized (B) and traditional (A) shea butter production processes have the largest embodied energy per kg of shea butter (175 and 172 MJ respectively) followed by the further improved-mechanized (E) (109 MJ), improved-mechanized (D) (106 MJ), and improved (C) (103 MJ) shea butter production processes. Firewood contributes the largest amount of total embodied energy to the production processes (94-100% or 172 MJ for processes A and C and 103 MJ for processes B, D, and E). Although firewood is often excluded from EIO-LCAs in the developed world, it has significant impact there because of greater deforestation and related environmental impacts that are combined with minimal regeneration policies (Afrane and Ntiamoah, 2012; Ekeh et al., 2014).

Nevertheless, excluding the embodied energy of firewood to reveal the other important environmental components of the shea butter production process and further comparison to traditional EIO-LCA methodology, the embodied energy associated with the diesel fuel and engine oil to operate machines in processes B, D, (1,600 KJ/kg) and E (2,800 KJ/kg) is greatest (47% of total embodied energy excluding firewood) followed by the transportation of materials

(820 KJ/kg for processes B and D and 1,600 KJ/ kg for process E or 24-27%) p), maceration, milling and extraction machines (760 KJ/kg for processes B and D and 950 KJ/kg for process E or 15-22%), housing materials for machinery (250 KJ/kg for processes B and D and 650 KJ/kg for process E or 7-11%), and construction, installation and repair (1.8 KJ/kg for processes B and D and 4.1 KJ/kg for process E or 0.05-0.07%). Moreover, when the embodied energy associated with firewood use is excluded, the embodied energy for the traditional and improved shea butter production processes (A and C) is zero. In rural areas, women are not paid hourly for shea butter production but per kg of shea butter or nuts sold. However, a large percent of shea butter produced is consumed locally (51% of shea butter in this study, N=141) that does not contribute to the cash economy accounted for in the EIO-LCI. However, when human energy is added to the EIO-LCA embodied energy excluding firewood, human energy was found to constitute 25-100% of the total energy (see Figure 3). From Figure 3, it is apparent that increased mechanization can reduce human energy without a large increase in total energy. This is because most infrastructure (machines and housing material) have low embodied energy over a ten-year life span.

Figure 3. Total human and embodied energy of the shea butter production processes excluding firewood.

When comparing the embodied energy output from the EIO-LCA to the process-based LCA excluding firewood (see Figure 4), the machines category is the largest contributor in the process-based LCA (950 KJ/kg or 59% of total embodied energy excluding firewood) then diesel and oil (350 KJ/kg or 22%). Transportation is shown to have a very low embodied energy in the process-based LCA (9.2×10^{-4} KJ/kg or <1.0%) compared to the EIO-LCA. Overall, the mechanized production processes (B and D) have over twice the total embodied energy in the EIO-LCA (3,500 KJ/kg of shea butter) than the process-based LCA (1,600 KJ/kg) (see Table A.15). In other studies that compared EIO-LCA to process-based LCA, they often find EIO-LCA has higher values because EIO-LCA has less truncation issues as it encompasses the whole economy (Suh and Hupples, 2005; Majeau-Bettez et al., 2011). This was the case for the embodied energy of two categories in the EIO-LCA (diesel and oil and transportation) in this

research that were higher than the process-based LCA values. However, the machine and housing categories in the process-based LCA are slightly higher than the EIO-LCA but this is a small difference (190 and 54 KJ/ kg respectively).

Figure 4. Comparison of embodied energy (KJ/kg of shea butter) between process-based and EIO-LCAs in the different material categories associated with the traditional and improved mechanized shea butter production processes (B and D). Manual shea butter production processes (A and C) are not included because firewood is not considered to have embodied energy in traditional process-based LCA and, thus, their embodied energy is zero. Sensitivity bars represent the range in embodied energy given different extraction rates reported in the literature (Jibreel et al., 2013; Jasaw et al., 2015; Adams, 2015).

Thus, with similar and more encompassing results, EIO-LCA may be recommended in similar locations with limited resources and data accessibility because the LCI is less time and labor intensive than the process-based LCA (Suh and Huppel, 2005; Junnila, 2006). Additionally, many process-based LCA databases do not include labor services of housing

construction, machine installation and repair like EIO-LCA. Even though labor services contributed less than 1.0% of the total EIO-LCI embodied energy in this study, they could be significant in other applications especially in developing countries with more labor intensive economic systems or in developed countries with higher cost of labor.

Although other studies have compared EIO-LCA and process-based LCA, this is the first study to compare the two methods in a developing country as the other LCA comparison studies were based on developed countries and databases (Hendrickson et al., 1997; Suh and Huppes, 2005; Junnila, 2006; Majeau-Bettez et al., 2011; Zhang et al., 2014). Nevertheless, this doesn't mean that EIO-LCA is better than process-based LCA or hybrid LCA approaches, but may be the only practical method available with limited resources. In general, selection of an appropriate LCI method is dependent on the goal and scope of the LCA (Suh and Huppes, 2005). For example, process-based LCA is more developed to assess other impact categories available outside of embodied energy than EIO-LCA (Suh and Huppes, 2005) and was also employed in this study.

3.3 Process-based LCA

Figure 5 displays results of the impact assessment in global warming potential (GWP), human toxicity (HT), and abiotic depletion (AD) categories for the shea butter production processes. Similar to embodied energy, the traditional production processes (A and B) have the largest GWP (18 and 19 kg CO₂ eq/kg of shea butter respectively) compared to the improved processes (C and D) (11 kg CO₂ eq/kg) because of the higher contribution of firewood (99-100% of all processes). The other categories (machines, housing, diesel and oil, and transportation) only contribute a total of 0.12 kg CO₂ eq/kg to the GWP of the mechanized shea butter production processes (B and D). However, when considering higher firewood measurements

from other studies (Jibreel et al., 2013; Adams, 2015), the GWP for the improved shea butter production process is close to the traditional process as shown by the sensitivity bars in Figure 5. The traditional processes may even have less GWP than the improved processes, if the traditional roasters have lower emissions than the three-stone fire.

Figure 5. Process-based LCA results of the CML-2001 global warming potential 500a, abiotic depletion, and human toxicity 500a impact categories for four different shea butter production processes (A-D) and associated material categories. Sensitivity bars represent the range of values given: (1) firewood measured from other studies for the improved process (Ojeda, 2009; Adams, 2015; Jasaw et al., 2015), (2) doubling of shea butter processed by macerating and milling machines, (3) higher firewood emissions measured in the field (Roden et al., 2009), and (4) assuming the traditional shea roaster had lower emissions than the three stone fire (Jetter et al., 2009).

In the HT impact category, the traditional-mechanized shea butter production process B has the largest HT (0.15 1,4-DB eq/kg) followed by the improved-mechanized process D (0.13 1,4-DB eq/kg) then the traditional process A (0.041 1,4-DB eq/kg) and improved process B (0.025 1,4-DB eq/kg). Unlike with GWP, macerating and milling machines have a larger contribution to HT (0.076 1,4-DB eq/kg) than firewood (0.041 and 0.025 1,4-DB eq/kg for processes B and D respectively) followed by the machine housing materials (0.027 1,4-DB eq/kg) and diesel and oil (6.2×10^{-3} 1,4-DB eq/kg) for the mechanized shea butter production processes (B and D). Nevertheless, the traditional-mechanized process B still has higher total HT than the improved-mechanized process D because of the larger amount of firewood consumed and associated HT in the traditional process. Most of the HT in the machines category (51%) is attributed to aluminum production (0.039 1,4-DB eq/kg). However, since the machine and housing materials and diesel and oil are manufactured and extracted in other countries, they have more global than local impacts to HT than firewood (Cornejo et al., 2013).

For the AD category, the traditional and improved mechanized production processes (B and D) are the same (0.0015 kg Sb-eq/ kg of shea butter) because firewood does not contribute to

AD (the depletion of fossil and mineral resources). Thus, the abiotic depletion of the non-mechanized processes (A and C) are zero. Diesel and oil used by the machines in the mechanized production processes (B and D) depletes the most non-renewable resources (9.2×10^{-4} kg Sb eq/kg or 59% of total abiotic depletion for processes B and D) followed by macerating and milling machines (4.6×10^{-4} kg Sb eq/kg or 30%) and housing for the machines (1.7×10^{-4} kg Sb eq/kg or 11%). Over all the impact categories, transportation was negligible (4.1×10^{-10} kg Sb eq/kg or <1%). In general, the process-based LCA analysis highlights important environmental impacts of other materials used in the shea butter production process (diesel and oil and machines) than firewood.

3.4 Recommended Improvements for Sustainable Shea Butter Production

The primary aim of this study was to quantify and compare the environmental and human energy implications (a social issue) between traditional and improved shea butter production processes that have increased mechanization. Overall, the combined analysis points to important improvements needed in all five shea butter production processes investigated in this study to make them more environmentally and socially sustainable. Primarily, firewood was a substantial contributor to human and embodied energy, global warming potential, and human toxicity. Improved cookstoves have been reported to reduce fuel use by 47% as well as emissions of carbon monoxide by 70% (Jetter et al., 2009). The reduction of emissions and fuel use from an improved rocket stove was modeled for the different shea butter production process variations and were found to potentially reduce global warming potential by 78% (from 18 to 4.1 kg CO₂ eq/kg and 11 to 2.4 kg CO₂ eq/kg for the traditional, A and B, and improved, C and D, processes respectively) and human toxicity by 83% for the non-mechanized processes A and C (from 0.041 to 0.0071 1,4 DB eq/kg and 0.025 to 0.0042 1,4 DB eq/kg respectively) and 15-23% for the

mechanized processes B and D (from 0.15 to 0.12 1,4 DB eq/kg and 0.13 to 0.11 1,4 DB eq/kg respectively), and firewood embodied energy by 52% (from 170 to 82 MJ/kg for the traditional processes A and B and 103 to 49 MJ/kg respectively for the improved processes C and D). However, improved cookstoves have been designed primarily for household use so there is a need to design them for larger manufacturing purposes such as food processing. The replacement of firewood and charcoal with other fuel sources (e.g. natural gas, kerosene, electricity) may reduce local environmental impacts but will still have global impacts from extraction of fossil fuels. They are also currently economically infeasible compared to firewood as they require further processing and transportation costs (Afrane and Ntiamoah, 2012).

Compared to reductions in environmental impact categories, using improved cookstoves had a relatively small reduction in human energy (304 KJ/kg reduction for traditional processes A and B and 180 KJ/kg reduction for improved processes C-E which is a 3-14% reduction of total human energy depending on the process). Also, total energy associated with greater mechanization did not increase considerably but largely reduced the amount of required human energy. Thus, to reduce the most energy intensive steps of the shea butter production processes, there should be a focus on increasing access of women shea collectors to macerating, milling, and extraction machines as well as bicycles or donkey carts to reduce human energy from harvesting the shea fruit. Moreover, although the improved shea butter production processes had lower firewood usage and associated environmental impact and human energy, the human energy for other processing steps such as sun-drying and macerating the shea kernels was greater than the traditional processes. This increase in human energy for drying the shea nuts comes at a very busy time during the rainy, agricultural season with peak labor demands for weeding and harvesting which limits the agricultural production of societies primarily based on human labor

(Giampietro and Pimentel, 1990). In contrast, firewood is mostly collected during the dry season where the women do not need to tend to their fields. Better drying racks, solar driers and mechanized crushers could reduce the human energy in those steps. Overall, reducing human energy in the shea butter production process may facilitate further development of the shea industry, women's empowerment, and food security as women collectors will have more time, energy, and resources to collect more fruit and, thus, increase their shea butter production, generating more income for their families (Adams, 2015; FAO, 2015).

4. Conclusions

Many manufacturing processes in developing countries are undergoing changes from traditional to improved methods and are becoming more mechanized. It is imperative to understand the environmental and human energy implications particularly in the context of global climate change and achievement of the UN's Sustainable Development Goals. In general, human energy must be taken into account for assessing product sustainability in addition to environmental impacts. For example, jatropha oil used as a biofuel for electrification is reported to have lower environmental impacts than fossil fuels, but it has not been adopted in Mali because it is time intensive with little economic return (Grimsby et al., 2012). This study broadens the application of LCA methods and energy analysis in developing countries by incorporating environmental impacts of firewood and a social sustainability indicator (human energy) as tools for assessing sustainable human development. For example, the values and methodology in this research for shea butter production can be used as a baseline comparison for selecting and improving food processing particularly for world oil crops crucial to global food security (FAO, 2002). Moreover, EIO-LCA was found comparable to process-based LCA and

recommended when access to resources (time, money, data, and databases) are limited. As an outcome of this research, mechanization, use of improved cookstoves, sustainable firewood sourcing, and less human energy intensive transportation methods for shea fruit harvesting were recommended to reduce human energy and environmental impact and thus potentially increase women's shea butter production, empowerment, health, food security, and income in sub-Saharan Africa (Adams, 2015; FAO, 2015).

ASSOCIATED CONTENT

Appendix A. Supplementary Data Supplementary data (Figure A.1 and Tables A.1-A.15) can be found at <http://dx.doi.org/XXXXXXX>

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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