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Better practices for including traditional firewood in LCA: Lessons from a shea butter case study in Burkina Faso

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A R T I C L E I N F O

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A B S T R A C T

Firewood is a key energy source in developing countries, but its consideration for Life Cycle Assessment (LCA) purposes suffers from both data and methodological issues. A specific literature review revealed considerable variability in the way these issues have been addressed in existing studies. To improve current practices, a framework for proper inclusion of all environmental impacts related to traditional firewood uses is proposed, and a configurable dataset for other studies was produced. The framework was then applied to a case study on shea butter production, where firewood accounting appeared to be one of the main sources of discrepancies in the results of existing studies. For each parameter related to firewood uses and their impacts, data and methodological choices that LCA practitioners may face were then investigated through uncertainty and sensitivity analyses. Firewood consumption volumes and emission factors from firewood combustion proved to be the most critical parameters for all environmental issues, and the options explored in this study to tackle these data collection issues can be adapted to other case studies. Beyond data matters, the main methodological challenge for firewood accounting lies in estimating the fraction of firewood from non-renewable sources. Use of the default values from the spatially explicit supply-demand WISDOM model is recommended here. For the shea butter value chain in Burkina Faso, one of the main solutions for mitigating environmental impacts would be to reduce firewood consumption by promoting improved cookstoves, improving boiling practices, or replacing firewood with other biomass sources, such as shea nutshells.

1. Introduction

Bioenergy accounted for 10% of the world's primary energy supply in 2021, with more than one third being generally qualified as traditional bioenergy, defined by the International Energy Agency as "the use of solid biomass with basic technologies, such as a three-stone fire or basic improved cook stoves", mainly used in developing countries (IEA, 2022). Bioenergy is actually the main energy source in Africa, accounting for 48% of total primary energy demand in 2015 (IEA, 2017). Around 90% of the African bioenergy consumption is for cooking and heating, mostly as firewood or charcoal (IEA, 2017; UNEP and African Union, 2019).

Such traditional uses of bioenergy are commonly associated in the literature with major environmental issues such as deforestation,

Abbreviations: ABO, All-But-One; CCT, Controlled Cooking Test; CDM, Clean Development Mechanism; EF, Emission Factor; FFL, Fair-for-Life (certification scheme); fNRB, Fraction of Non-Renewable Biomass; GHG, Greenhouse Gas; ICS, Improved Cookstove; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; NMVOC, Non-Methane Volatile Organic Compounds; OAT, One-at-a-time; PM, Particulate Matter; PV, Photovoltaic; SD, Standard Deviation; SEM, Standard Error of the Mean; SOC, Soil Organic Carbon; TSF, Three-stone fire cookstove; UNFCCC, United Nations Framework Convention on Climate Change; WBT, Water Boiling Test; WISDOM, Woodfuels Integrated Supply/Demand Overview Mapping.

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climate change and household air pollution (IEA, 2022; Mardones and Cornejo, 2020; Masera et al., 2015; UNEP and African Union, 2019; United Nations, 2020). Beyond these global aspects, proposing solutions to mitigate the environmental issues related to firewood use generally means being able to assess them on the scale of specific processes. However, such assessments face both data and methodology issues, including a scarcity of data on firewood collection and use (Bailis et al., 2015; FAO, 2016), a lack of representativeness in the data available on stove performance (Lombardi et al., 2017; Zhang et al., 2017), or difficulty in attributing global deforestation trends to specific factors (Geist and Lambin, 2002).

These challenges are particularly problematic when carrying out Life Cycle Assessment (LCA) studies in developing and emerging countries. Despite its international recognition and use, LCA in these countries suffers from a lack of case studies, hence a lack of consideration of their specific methodological issues (Basset-Mens et al., 2021; He and Yu, 2020; Karkour et al., 2021; Mukoro et al., 2021; Ramjeawon, 2012). Traditional bioenergy is no exception and a recent review showed that, despite their importance in global energy consumption, traditional uses of firewood or charcoal in developing countries only accounted for 13% of LCA studies published between 2009 and 2018 on forest-derived solid biofuels (Musule et al., 2022). In terms of LCA methodology, considering bioenergy in developing countries can be very different from bioenergy in developed countries. Indeed, in developing countries, wood is often obtained directly from natural forests, making it a natural resource, while wood in developed countries generally comes from forestry or wood plantations, making it a product of human activities with land as the underlying natural resource (Alvarenga et al., 2013; Crenna et al., 2018). This difference in the status of wood extraction calls for the use of specific Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) procedures in developing countries, in order to effectively assess the environmental impacts of firewood uses.

In this context, the present work sought to contribute to better accounting of traditional firewood uses within the LCA framework. To that end, a review of current LCA practices regarding firewood inclusion was first carried out (section 2.1), and a general framework was proposed accordingly (section 2.2). The framework was then applied to an LCA case study on shea butter production in Burkina Faso (sections 2.3 and 3). In the case study, the specific focus was on methodological and data choices for considering firewood uses, and their influence on LCA results was evaluated through uncertainty and sensitivity analyses. Lastly, recommendations are provided for LCA practitioners concerning better practices for the inclusion of traditional firewood in LCA (section 4).

2. Material and methods

2.1. Critical review of current practices for including traditional firewood in LCA

For a clearer understanding of current practices related to the inclusion of firewood in LCA and to identify the best ones for building the related framework (see Section 2.2), a literature review on case studies involving traditional firewood was carried out. This was done by searching all combinations of keywords “Life Cycle Assessment” or “LCA”, and “firewood” or “fuelwood” in the title, abstract and keywords of scientific literature through the ScienceDirect® (https://www.sciencedirect.com/search) and Web of Science™ (https://www.webofscience.com/wos/woscc/basic-search) search engines. This review applied to the state of the art as of January 2023.

In all, 55 scientific publications were identified. Among these references, only the LCA case studies involving firewood uses in developing countries were considered, resulting in a final selection of 16 references. In particular, studies focusing on a single environmental issue, such as carbon footprints, were excluded, so as to properly review current practices on all environmental issues related to traditional firewood uses. Table 1 gives the main descriptive elements of these 16 publications. Fig. 1 summarizes how these studies addressed the contribution of firewood to climate change (see Supplementary Material A for details and results for pollutant emissions).

Table 1
General description of the selected LCA case studies involving traditional firewood.

Reference	Main product or service studied	Geographical scope	Firewood use
(Banerjee and Tierney, 2011)	Electricity and heat production	Rural villages in the state of Jharkhand, India	Fuel for heat production
(Afrane and Ntiamoah, 2012)	Cooking	Ghana	Fuel for cooking
(Singh et al., 2014)	Cooking	India	Fuel for cooking
(Brondani et al., 2015)	Biodiesel production	State of Rio Grande do Sul, Brazil	Fuel for steam production
(Dias Mayer et al., 2016)	Ethanol fuel production	Small-scale distilleries in Brazil	Fuel for ethanol distillation
(Botnen Smebye et al., 2017)	Biochar production	Rural tropical regions	Avoided product from biochar production
(Coltro et al., 2017)	Rice production	Southern Brazil	Fuel for rice drying and for electricity production
(Hussain et al., 2017)	Tobacco production	Pakistan	Fuel for tobacco curing
(Naughton et al., 2017)	Shea butter production	Mali	Fuel for shea nut roasting or boiling, and for butter extraction and refining
(Schmidt Rivera et al., 2018)	Cooking	Small communities in developing countries	Fuel for cooking
(Situmorang and Manik, 2018)	Tapioca, coffee and tofu processing	Toba Samosir Regency, Indonesia	Fuel for coffee roasting
(Pyay et al., 2019)	Intermediate rubber products	Thailand	Fuel for rubber sheet smoking
(Iswanto Wiloso et al., 2019)	Tempeh production	Western Java, Indonesia	Fuel for tempeh production
(Zappe et al., 2020)	Tobacco production	Southern Brazil	Fuel for tobacco curing and drying
(Mendieta et al., 2021)	Cane sugar production	One processing plant in Colombia	Fuel for workers' cooking and for heat production
(Pizarro-Loaiza et al., 2021)	Cooking	Rural Colombia	Fuel for cooking

Table 1 shows the diversity of LCA case studies involving traditional firewood, in terms of geographical scope and firewood use. However, the diversity is not necessarily representative of current uses of traditional bioenergy consumption, with only two out of these 16 studies carried out in Africa, despite the importance of that continent in global bioenergy consumption (Afrane and Ntiamoah, 2012; Naughton et al., 2017). In comparison, six studies were carried out in Asia and another six in South America. The last two studies were generic in terms of geographical scope. In terms of firewood use, six out of the 16 studies considered firewood as fuel for cooking (Afrane and Ntiamoah, 2012; Botnen Smebye et al., 2017; Mendieta et al., 2021; Pizarro-Loaiza et al., 2021; Schmidt Rivera et al., 2018; Singh et al., 2014). The other studies considered firewood as a fuel in transformation processes, mostly for heat production.

Related assumptions and data sources were not always detailed when considering the inclusion of firewood environmental impacts: for three out of the 16 studies, it was not possible to determine whether firewood contributed to climate change and, for four studies, no details on pollutant emissions were provided. In most of the studies (7 out of 16), firewood was considered not to contribute to climate change. Among

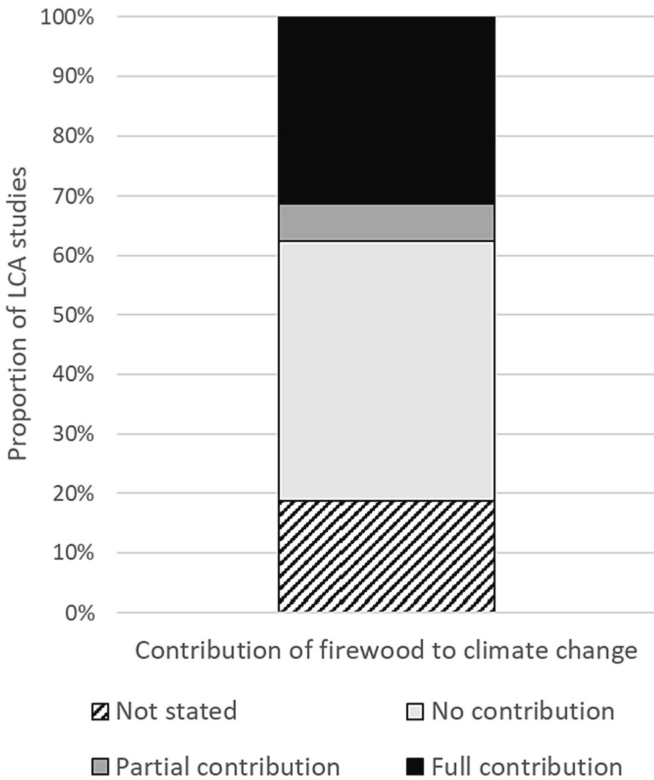

Fig. 1. Current practices regarding the inclusion of traditional firewood impacts on climate change in published LCA studies involving firewood uses in developing countries.

these studies, four justified this assumption by a specific firewood supply, such as a wood plantation, wood scrap, or wood from agricultural land clearing (Afrane and Ntiamoah, 2012; Banerjee and Tierney, 2011; Iswanto Wiloso et al., 2019; Zappe et al., 2020), but three did not provide any details (Coltro et al., 2017; Mendieta et al., 2021; Pizarro-Loaiza et al., 2021). Conversely, five studies considered that all firewood came from non-renewable sources and therefore fully contributed to climate change (Botnen Smebye et al., 2017; Hussain et al., 2017; Naughton et al., 2017; Schmidt Rivera et al., 2018; Situmorang and Manik, 2018). Only one study compared local firewood consumption and potential sustainable supply to estimate the fraction of firewood consumption actually contributing to climate change (Singh et al., 2014).

The rationale of firewood impact on climate change is that a non-renewable supply contributes to deforestation, which also has other environmental impacts considered in LCA, such as biodiversity losses. However, of the six studies that considered a partial or full contribution of firewood to climate change, only one modeled a corresponding land transformation from forest to arable (50%) or shrub (50%) land, based on average aboveground biomass density (Botnen Smebye et al., 2017).

2.2. *Formalizing a framework for traditional firewood inclusion in LCA*

Based on the best practices observed in the literature (see Section 2.1), the Life Cycle Inventory (LCI) fluxes accounted for when modeling traditional firewood uses should include:

- Greenhouse Gas (GHG) emissions from firewood combustion, considering whether or not firewood comes from renewable sources. The proportion of firewood actually contributing to climate change is usually referred to as the fraction of Non-Renewable Biomass (fNRB) in Clean Development Mechanism (CDM) projects (UNFCCC/CCNUCC, 2020).
- Non-GHG emissions from firewood combustion.
- Land transformations associated with potential deforestation due to non-renewable firewood uses, and their environmental consequences.

For land transformations, while biodiversity losses through habitat loss are generally considered in current LCIA methods, changes in carbon storage are not (Flynn et al., 2012; Milà i Canals and de Baan, 2015). Soil Organic Carbon (SOC) losses, and related N-compound emissions due to deforestation should thus be included when modeling firewood uses. However, if land is not used after deforestation, or if the new land use is not known, the potential SOC loss might be difficult to estimate. For instance, the Tier 1 guidelines from the Intergovernmental Panel on Climate Change (IPCC) for national GHG inventories assume the same SOC stock level between forest land and unused grassland (Dong et al., 2019).

Let us suppose that land is used after deforestation, such as for crop expansion. In that case an allocation issue arises, and it then has to be decided according to the context whether deforestation impacts, including SOC loss, are allocated to firewood or new land use. The choice made should be explicitly stated and justified, and fNRB should be calculated accordingly: if deforestation is allocated to new land use, the related amount of firewood can be considered as waste biomass and not as a non-renewable biomass supply, the opposite being the case if deforestation is allocated to firewood.

The resulting framework proposal for firewood inclusion in LCA is shown in Fig. 2. The framework is also available as an LCI dataset for LCA practitioners, where default values and data sources are provided for all input parameters (Benoist et al., 2023). This dataset can be imported into SimaPro via ELDAM software (Coste et al., 2021).

2.3. *LCA case study*

2.3.1. *Choice of case study*

The purpose of the LCA case study was to test the proposed framework for firewood inclusion and better understand the influence of related methodological and data choices. Of the different products or services identified in section 2.1, shea butter production was interesting as it related to one of only two studies carried out in Africa (Naughton et al., 2017). Indeed, shea trees grow exclusively in Africa, and especially West Africa, with Nigeria, Mali and Burkina Faso being the main producers in 2020 (FAO, 2022). Shea is a commodity for both local consumption and for export, especially for food and cosmetic purposes: according to the Global Shea Alliance, in 2018 57% of shea production was used for local consumption, and 43% was exported (Bockel et al., 2020; Lovett, 2015).

In addition to the study by Naughton et al. (2017), one other LCA case study and two carbon footprints were found in the literature (Bockel et al., 2020; Ewemoje and Oluwaniyi, 2016; Glew and Lovett, 2014). These studies differed in terms of environmental issues, system boundaries, countries, allocation procedures, or technological routes considered (see Supplementary Material B for details). However, apart from Ewemoje and Oluwaniyi (2016), who carried out a gate-to-gate analysis focusing on a mechanized industrial process, all the other studies pointed out the major relative contribution made by firewood uses to the impacts of shea butter production while yielding very different absolute results. Assumptions regarding firewood inclusion might explain some of these differences, but the assumptions and data used to take it into account were unfortunately insufficiently explained to confirm this hypothesis (see Supplementary Material B). Shea butter production was therefore chosen as an interesting case study to apply the proposed framework and investigate the influence of data and modeling choices.

2.3.2. *Goal and scope*

The goal of this LCA case study was to identify the main

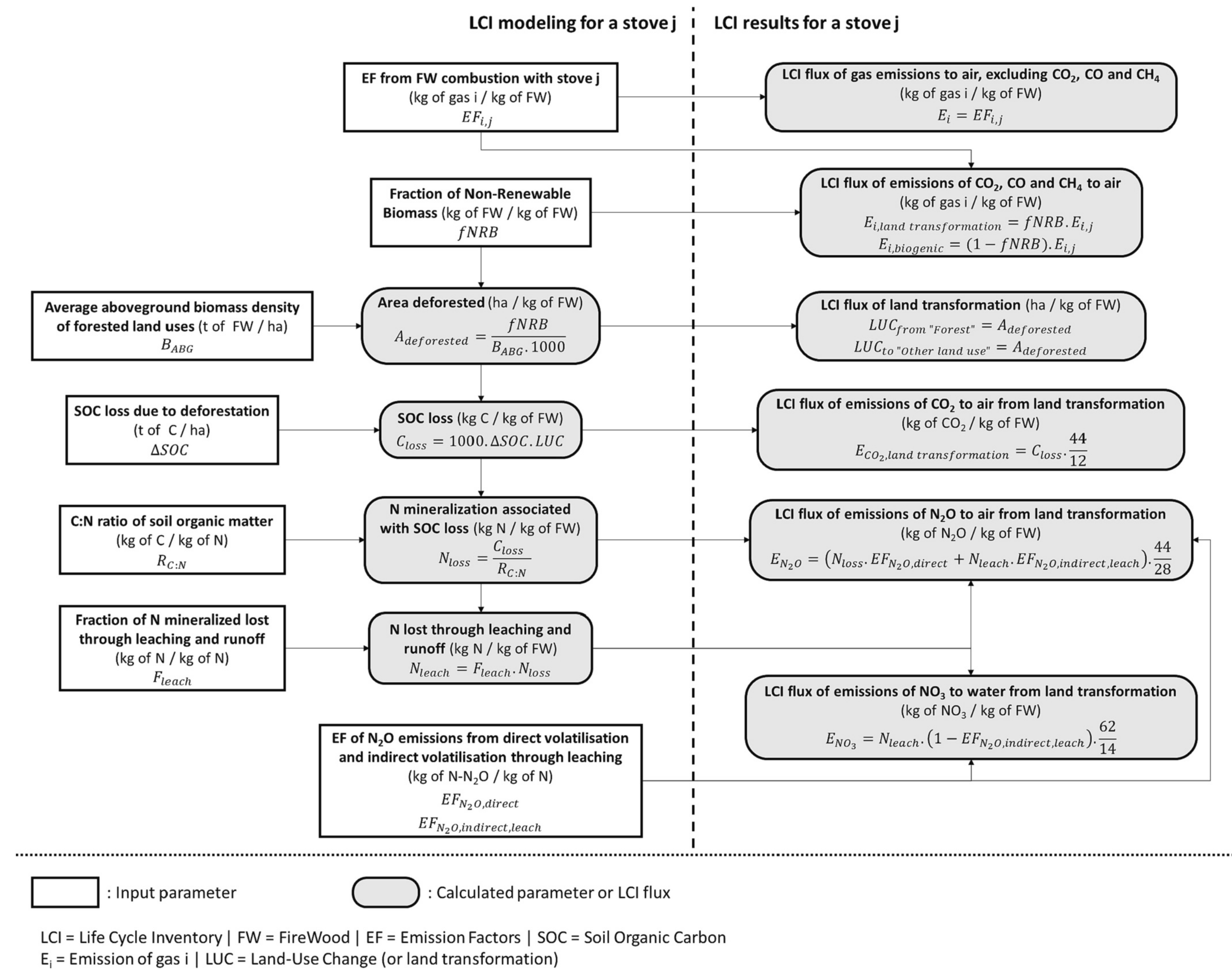

Fig. 2. Framework proposal for the inclusion of traditional firewood in LCA.

environmental impacts of mechanized shea butter production for cosmetic use, and the main sources of those impacts. The system boundaries included all production and transportation steps from shea fruit collection to shea butter refining, but excluded cosmetics production, use and end-of-life (see Fig. 3). The chosen functional unit was one kilogram of refined shea butter at the factory gate in Saint-Léonard, France.

The intended scope of the study was to represent current production of refined shea butter under Fair-for-Life (FFL) certification by OLVEA, a French company working in the vegetable and fish oil sectors, representing several thousand tons of refined shea butter per year. The main data source for this study was therefore primary data from OLVEA, in particular the 2019 operating data for their factories of shea butter production in Bobo-Dioulasso, Burkina Faso, and shea butter refining in Saint-Léonard, France. Where necessary, secondary data from the literature were used, especially for shea kernel production (see section 2.3.3 and Supplementary Material C). Finally, the *ecoinvent* database version 3.6 (cut-off version) was used for the description of background processes.

The Life Cycle Inventory (LCI) was modeled with *SimaPro* software (version 9.1.1.1), following an attributional perspective (EC-JRC, 2010). Economic allocation procedures were used to solve multifunctionality. For LCIA, the Product Environmental Footprint method was used (Fazio et al., 2018), based on the *EF 3.0 method (adapted)* version implemented in *SimaPro* software. Both single score and midpoint results were used, to select the key environmental issues of the system and to further analyze the results, respectively, including contribution, uncertainty and sensitivity analyses.

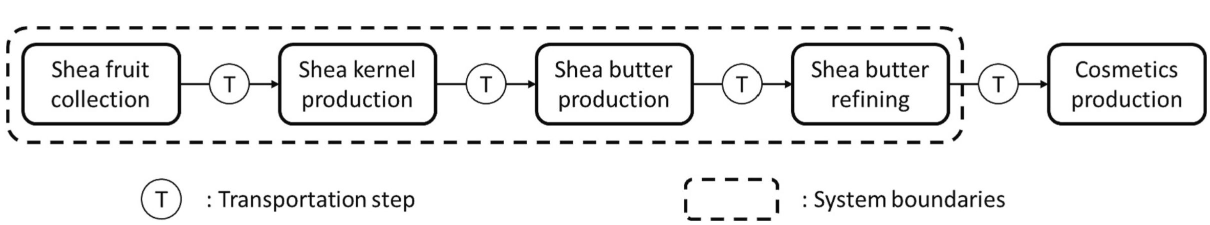

Fig. 3. Simplified diagram of shea butter production for cosmetic use and definition of the system boundaries for the LCA case study.

2.3.3. Life cycle inventory (LCI)

In this section, the overall production process from shea fruit collection to shea butter refining is briefly described (see Fig. 4). A detailed description of data and sources used is given in Supplementary Materials C and D.

The supply area of the OLVEA factory in Bobo-Dioulasso for shea nuts under FFL certification includes four regions in southwest Burkina Faso: Hauts-Bassins, Sud-Ouest, Cascades, and Centre-Ouest. Since shea trees do not receive any inputs in these zones, no cultivation process was considered. After picking, shea fruits are transported to nearby settlements where they are pulped to obtain the nuts. Shea nuts are then boiled, dried and shelled before storage. Heat requirements for boiling are provided by firewood. Boiling is generally performed with a traditional three-stone fire (TSF) cookstove but, since 2016, the Carbon Balanced program promoted by L'Oréal and OLVEA has helped to disseminate in the area an improved cookstove (ICS), called *Roumdé Ouaga métallique 30*, used by some collectors instead of TSF.

After storage, shea kernels are collected and sent to the OLVEA factory in Bobo-Dioulasso, Burkina Faso, where they are crushed and pressed to produce crude shea butter, which undergoes a first filtration. The heat requirements of the process are covered by the combustion of shea cakes, which are the main by-product of kernel milling. Ten percent of the electricity needs are met by photovoltaic (PV) panels, and the rest is supplied by the national electricity grid.

After packing, crude shea butter is sent by train to Abidjan, Ivory Coast, then by boat to Le Havre, France, and finally by truck to Saint-Léonard, France, where the OLVEA refining unit is located. Shea butter is then neutralized, bleached and deodorized. The energy requirements of the process are covered by natural gas for heat, and by certified renewable sources (89%), local PV panels (6%) and the national grid (5%) for electricity.

2.3.4. Sensitivity analyses and estimation of uncertainties related to firewood uses

Including firewood uses in LCA requires the LCA practitioner to specify all input parameters defined in the framework proposed in Fig. 3, which can be used to assess the impacts associated with the use of 1 kg of firewood, and the firewood consumption of the value chain studied. The objective of the uncertainty and sensitivity analyses carried out in this work was to highlight the most critical methodology or data choices for determining these parameters, based on the specific case of shea butter production in Burkina Faso.

As explained in the previous section 2.3.3, firewood uses in this case study arise during shea nut boiling, involving either a traditional TSF or the specific ICS promoted in the region. The framework proposal therefore had to be applied to both cookstoves, but the only difference lies in the Emission Factors (EF) used (noted $EF_{i,j}$ for a gas i with stove j in Fig. 2). All other parameters of the framework refer to the firewood supply, which could be assumed to be the same in both cases.

Three types of data were thus needed to determine total firewood consumption: the firewood consumed for shea nut boiling with TSF and with ICS, and the relative proportions of nuts boiled with each cookstove. Unfortunately, no data were available on the firewood consumption of the considered ICS specifically for shea nut boiling. This information was thus deduced from the firewood consumption for shea nut boiling with TSF, and the relative efficiency of ICS compared to TSF in terms of reduced firewood consumption.

Of all these parameters, the uncertainty and sensitivity analyses focused on six:

- The three parameters related to firewood consumption: consumption of TSF, reduced consumption of ICS, and the fraction of nuts boiled with ICS; and.
- Three parameters, or set of parameters, of the framework: EF, fNRB and the average aboveground biomass density.

For the other parameters of the framework, corresponding to SOC issues and related N losses (see Fig. 2), specific analyses and recommendations can be found elsewhere in the literature (Bessou et al., 2019).

For each of the six parameters considered, two or three options were defined, generally representing choices to be made between data sources, and where possible, the uncertainty inherent to each option was quantified. Table 2 summarizes the different options considered for each parameter and the uncertainty associated with each of them. A base option was defined for each parameter. The options considered and data sources used are briefly described below for the three most important parameters for the results of the uncertainty and sensitivity analyses (see section 3.2 and 3.3): firewood consumption of TSF, EF from firewood combustion, and fNRB. Detailed descriptions and justifications for all six parameters are provided in Supplementary Material D.

According to data in the literature, shea nuts are generally boiled in batches of 10 to 60 kg with TSF (Adams, 2015; Gueye, 2011; Noumi et al., 2013), amounting to several hundred thousand operations performed per year, for the production of the several thousand tons of shea nuts under FFL certification. In the case of the OLVEA supply chain, several tens of thousands of collectors, generally women, are in charge of the nut boiling process. Each of them potentially has their own boiling practice, despite the common recommendations of the OLVEA staff regarding, for instance, boiling time. This potentially creates high

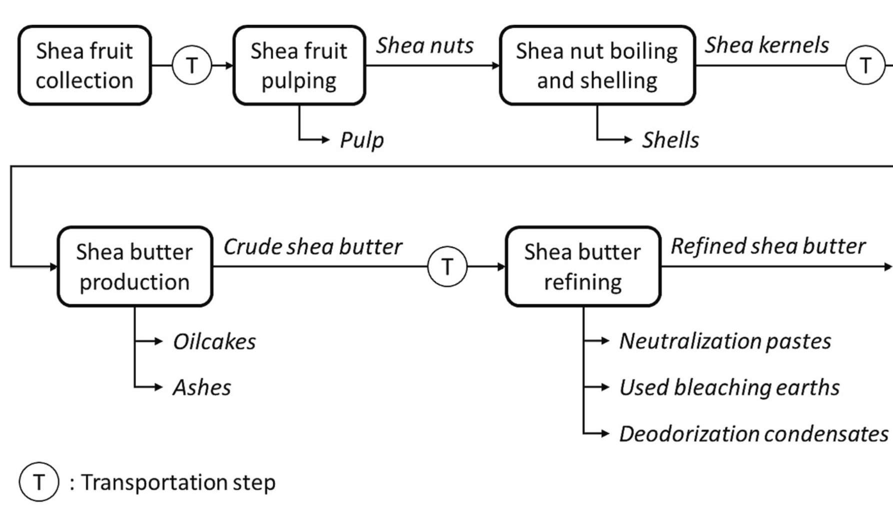

Fig. 4. Overview of the shea butter value chain under study and the main by-products.

Table 2
Summary of the options, base value and uncertainties considered for each firewood-related input parameter.

Input parameter	Option		Base value	Associated uncertainty	References
Firewood consumption of TSF	Base option	Field measurements	0.55 kg of firewood per kg of nuts	Normal distribution with a relative standard deviation (SD) of 19.7%	(Adams, 2015; Gueye, 2011; Jasaw et al., 2017; Johnson and Bryden, 2012; Naughton, 2016; Ojeda, 2009)
	Alternate option	Controlled Cooking Tests (CCT) data	0.17 kg of firewood per kg of nuts	Normal distribution with a relative SD of 4.7%	Data from the Carbon Balanced program
Reduced firewood consumption of ICS compared to TSF	Base option	CCT and Water Boiling Tests (WBT) data	47.5%	Normal distribution with a relative SD of 4.7%	Data from the Carbon Balanced program and (Sanogo, 2008)
	Alternate option	Survey data	28.3%	No uncertainty distribution	(Bensch et al., 2015)
Fraction of nuts boiled with ICS	Base option	Carbon Balanced data	15.1%	Normal distribution with a relative SD of 13.3%	Data from the Carbon Balanced program
	Alternate option	Carbon Balanced and literature data	6.5%	Product of two normal distributions – See Supplementary Material D	Data from the Carbon Balanced program and (Adams, 2015; Gueye, 2011)
Emission factors for firewood combustion	Base option	Laboratory data	See Supplementary Material D	Normal distribution	(Bilsback et al., 2019)
	Alternate options	CCT data completed by laboratory data	See Supplementary Material D	Normal distribution	Data from the Carbon Balanced program and (Bilsback et al., 2019)
		CCT data completed by modified laboratory data	See Supplementary Material D	Normal distribution	Data from the Carbon Balanced program and (Bilsback et al., 2019)
Fraction of non-renewable biomass (fNRB)	Base option	WISDOM model at national level	47.1%	Uniform distribution from 34.8% to 47.1%	(Bailis et al., 2015)
	Alternate options	WISDOM model at regional level	57.6%	Uniform distribution from 43.8% to 57.6%	(Bailis et al., 2015)
		Clean Development Mechanism (CDM) calculation tool	90%	No uncertainty distribution	(UNFCCC/CCNUCC, 2012)
Average aboveground biomass density of forested land uses	Base option	Data from the National Forest Inventory of Burkina Faso	95.6 t of dry firewood per ha	Normal distribution with a relative SD of 1.4%	(MEEVCC, 2016)
	Alternate option	IPCC Tier 1 default value	69.6 t of dry firewood per ha	Normal distribution with a relative SD of 68.2%	(Dong et al., 2019)

variability in boiling performance, including firewood consumption. Unfortunately, such data are scarce: in the case of shea nut boiling with TSF in southern Burkina Faso, only two measurements are available (Gueye, 2011).

To overcome this lack of data, two strategies were considered here: broadening the geographical coverage beyond Burkina Faso, or including indirect measurements. In both cases, the risk was to include unrepresentative data, due to spatial variability in the first case, or to inadequate measurement techniques in the second case. In the first case, which was chosen as the base option, supplementary field measurement data were collected from two neighboring countries, Ghana and Mali (Adams, 2015; Jasaw et al., 2017; Johnson and Bryden, 2012; Naughton, 2016; Ojeda, 2009). In the second case, data from Controlled Cooking Tests (CCT), from the Carbon Balanced program, whose original purpose was to assess relative performances between TSF and ICS, were used. In both cases, since the desired data were an average value, according to the central limit theorem, uncertainty was assumed to follow a normal distribution, centered on the mean value of collected data, with a standard deviation (SD) equal to the estimated standard error of that mean (SEM).

Regarding EF for firewood combustion, two types of data sources were identified: on the one hand, laboratory data (Bilsback et al., 2019), which have the advantage of being repeatable and quite exhaustive in terms of pollutants, but acquired under controlled conditions, which can differ from actual conditions (Bilsback et al., 2018; Lombardi et al., 2017), and on the other hand, measurements from CCT, which are carried out under conditions closer to reality, but are more variable and less exhaustive, considering only CO_2, CO, particulate matter (PM), and black and organic carbon emissions. In the context of an LCI calculation, the LCA practitioner must, therefore, make a compromise: using the most consistent and exhaustive dataset, consisting of laboratory data in this case, or using the most representative dataset, consisting of CCT data. In this work, in order to compare these two options despite the differences in the substances considered, CCT data were completed for missing pollutants. Two approaches for completion were considered: using raw laboratory data, or modified laboratory data, for which the differences observed between laboratory and CCT measurements for common emissions were used to extrapolate some emission factors (see Supplementary Material D). Of these three different strategies, it was decided to use laboratory data as the base option, since it was the most likely to be selected by an LCA practitioner as being easier to implement and not involving any modification of the initial dataset. In all strategies, the inherent uncertainties of the datasets were assumed to follow a normal distribution centered on mean values with an SD equal to the estimated SEM of collected data.

Lastly, for fNRB calculations, two main methodologies are available in the literature: the 'Woodfuels Integrated Supply/Demand Overview Mapping' (WISDOM) model, based on a spatially explicit analysis of firewood supply and demand, and the methodological tool proposed by the United Nations Framework Convention on Climate Change (UNFCCC) as part of the assessment of Clean Development Mechanism (CDM) projects (Bailis et al., 2015, 2017; UNFCCC/CCNUCC, 2020). Both approaches propose default values, especially useful for LCA practitioners, which were used here. In this work, the WISDOM model was considered the most advanced approach available and was chosen as the base option, notably the default value at national level. The two other possible options considered in this work were the default values from the WISDOM model at regional level, and from the CDM calculation tool. Both approaches are subject to uncertainties, although they may be challenging to quantify. In the case of the CDM calculation tool, no indication regarding uncertainties is provided and no uncertainty distribution is therefore associated with the default value. In the case of the WISDOM model, uncertainties were addressed by the authors providing minimum and expected values (Bailis et al., 2015). Without conclusive evidence on the distribution of these uncertainties, a uniform distribution between these two values was thus assumed, the expected value being considered as the base value.

2.3.5. Uncertainty analysis

The different uncertainty sources given in Table 2 were propagated to LCA results through the Monte Carlo method, based on 50,000 runs. Since the focus of this study was on the parameters involved in firewood use accounting, all other uncertainty sources were set to zero. Two approaches were used to estimate the contribution of each input parameter, or group of input parameters, in Fig. 2 to the uncertainties of LCA results (JCGM, 2008, p. 58):

- A one-at-a-time (OAT) approach, where all input parameters but one were set to their base value; the related sensitivity coefficient was then defined as the ratio between the resulting standard deviation of LCA results and the total standard deviation.
- An all-but-one (ABO) approach, where only one input parameter was set to its base value; the related sensitivity coefficient was then defined as 1 minus the ratio between the resulting standard deviation of LCA results and the total standard deviation.

Neither approach was able to provide an exact sensitivity coefficient, but by using both approaches together a potential range of sensitivity coefficients could be estimated, with ABO coefficients underestimating actual values by excluding all interaction effects, and OAT overestimating them by fully attributing all interaction effects to the considered parameter.

3. Results

3.1. Base results

Fig. 5 shows the relative contribution made by midpoint categories to the single score indicator from the *EF 3.0 method*, for the selected functional unit, i.e., one kilogram of refined shea butter at the factory gate in Saint-Léonard, France. Two impact categories accounted for more than 50% of the single score result, and seven more than 90%: human toxicity related to carcinogenic effects, due to pollutant emissions to air, water and soils along the value chain (29%), climate change (26%), use of mineral and metal resources (13%), photochemical ozone formation (10%), human toxicity related to non-carcinogenic effects (5%), use of fossil resources (4%), and particulate matter (4%). The following results focused on these midpoint categories, but complete results are available in Supplementary Material E.

Based on these results, Fig. 6 provides the contributions of the life cycle stages to the seven key midpoint impact indicators identified in Fig. 5. Shea kernel production was found to be the largest contributor to five impact categories: human toxicity related to carcinogenic (99%) and non-carcinogenic (97%) effects, photochemical ozone formation (84%), climate change (78%), and particulate matter (61%). For all these indicators, more than 95% of the impacts of kernel production were due to the combustion emissions from firewood consumption for nut boiling. The individual contributions of all other stages to these five impact categories fell below 7%, except shea butter transportation (10%) for photochemical ozone formation, shea butter refining (9%) for climate change, and shea butter production (13%), transportation (10%) and refining (9%) for particulate matter. In each of these cases, most of these contributions were linked to fossil fuel combustion for transportation, heat, or electricity.

In terms of resource use, fossil fuel consumption mainly took place mainly during shea butter refining (48%), mostly as natural gas for heat generation, shea butter production (26%), mostly for electricity production, and shea butter transportation (17%), by boat (56%), train (39%) and truck (5%). Lastly, the use of minerals and metals was mainly related to the construction of OLVEA facilities, for shea butter production (48%) and refining (44%).

3.2. Uncertainty analyses

Fig. 7 shows the uncertainty results, obtained by the Monte Carlo method, for key midpoint indicators. Compared to the previous Fig. 6, the two resource use indicators are not displayed for reasons of simplicity, as they were not affected by any of the uncertainty sources considered. The resulting uncertainty ranges are represented in a whisker diagram by the median, the first and third quartiles, and the 90% confidence interval. These results are reported in relative terms, compared to the base results outlined in the previous section 3.1. As those base results were obtained from the base options and base values presented in Table 2, they could differ from the mean and median uncertainty results, which was the case for the climate change indicator due to the fNRB parameter, whose base value corresponded to an extreme value. For all five indicators considered, the mean uncertainty results, not displayed in Fig. 7, differed by less than 3% from the median results.

The uncertainty results obtained showed that the 90% confidence intervals represented 49% of the base results for climate change, 66% for non-carcinogenic human toxicity, 67% for particulate matter, 72% for photochemical ozone formation, and 111% for carcinogenic human toxicity. For all indicators, the 50% confidence interval was 41% of the 90% confidence interval.

For a clearer understanding of what mostly caused these uncertainties, Fig. 8 provides the sensitivity coefficients estimated for the different parameters or groups of parameters, presented in Table 2. The minimum and maximum values of the coefficients, obtained by the ABO and OAT approaches, respectively, as well as a mean value, are presented.

The results in Fig. 8 highlight that the input parameters contributing most to the uncertainties in LCA results were the firewood consumption of TSF and the EF for firewood combustion. In the case of climate change, fNRB could also make a not insignificant contribution to the uncertainties, to a similar extent as EF, but both well behind the

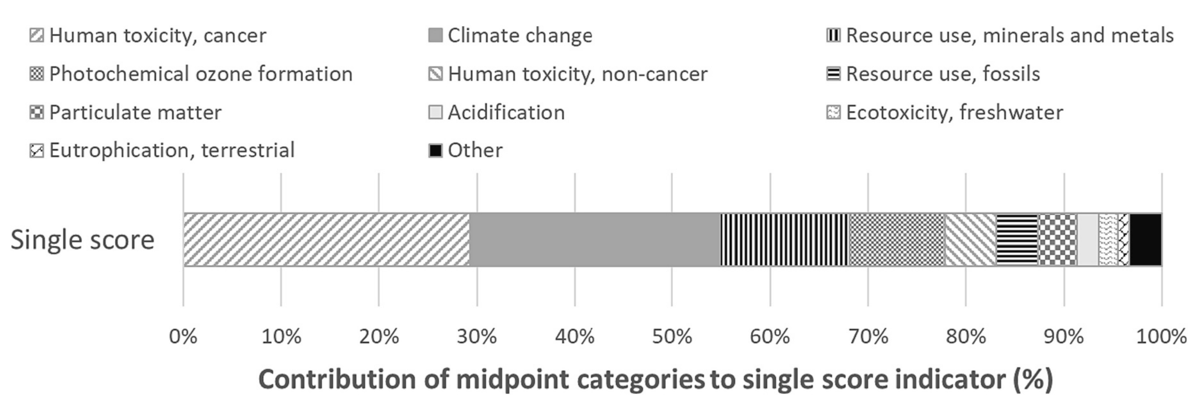

Fig. 5. Single score indicator results from the EF 3.0 method for one kilogram of refined shea butter at the factory gate, for all base options and base values.

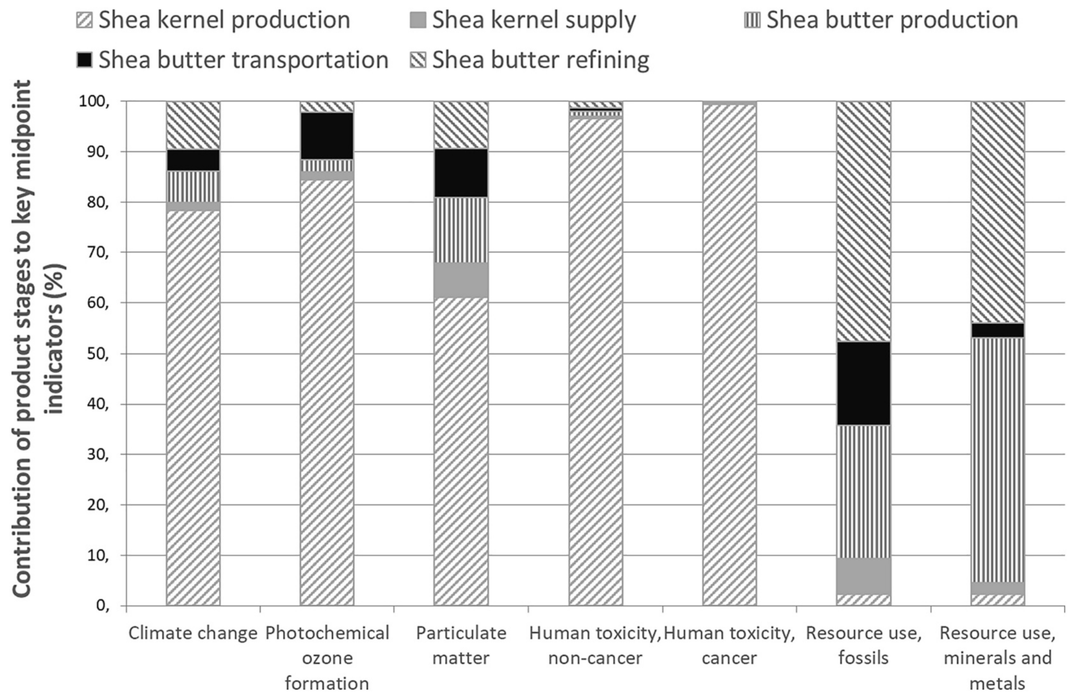

Fig. 6. Focus on key midpoint indicator results from the EF 3.0 method for one kilogram of refined shea butter at the factory gate, for all base options and base values.

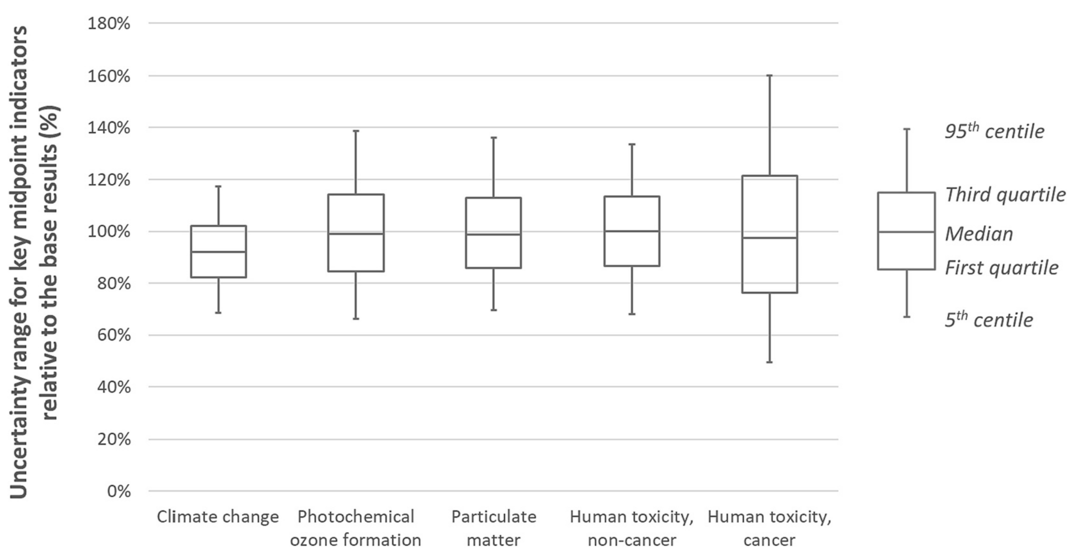

Fig. 7. Uncertainty results for key midpoint indicators relative to the base results (EF 3.0 method) for one kilogram of refined shea butter at the factory gate.

firewood consumption of TSF. All other parameters contributed marginally to the LCA uncertainties, for all indicators combined, with the largest ABO coefficient found at 7% for the average aboveground biomass density of forested land uses on the land use indicator (see Supplementary Material E).

3.3. Sensitivity analyses

Fig. 9 gives the results of the sensitivity analyses, in terms of median results and 90% confidence intervals. All results are expressed relatively to the median base results, consisting of the base options described in Table 2.

Fig. 9 shows that using CCT data instead of field measurements to estimate the firewood consumption of TSF had a strong effect on LCA results, both in terms of median and confidence interval range, with observed decreases for key indicators of 40% to 69%, and 75% to 89%, respectively. Conversely, switching data sources to estimate the reduction of firewood consumption due to ICS, the fraction of nuts boiled with ICS, or the aboveground biomass density of forested land uses had very little effect on LCA results, with differences below 5% for both medians and confidence intervals.

As regard EF for firewood combustion, the observed effects varied substantially depending on the indicators considered. When CCT data were used for only the few substances measured (CO_2, CO, PM, black and organic carbon), no effect was observed on climate change, photochemical ozone formation, and human toxicity related to carcinogenic effects. The effect of switching sources was somewhat greater for particulate matter, with a 20% decrease in the median and 58% in the

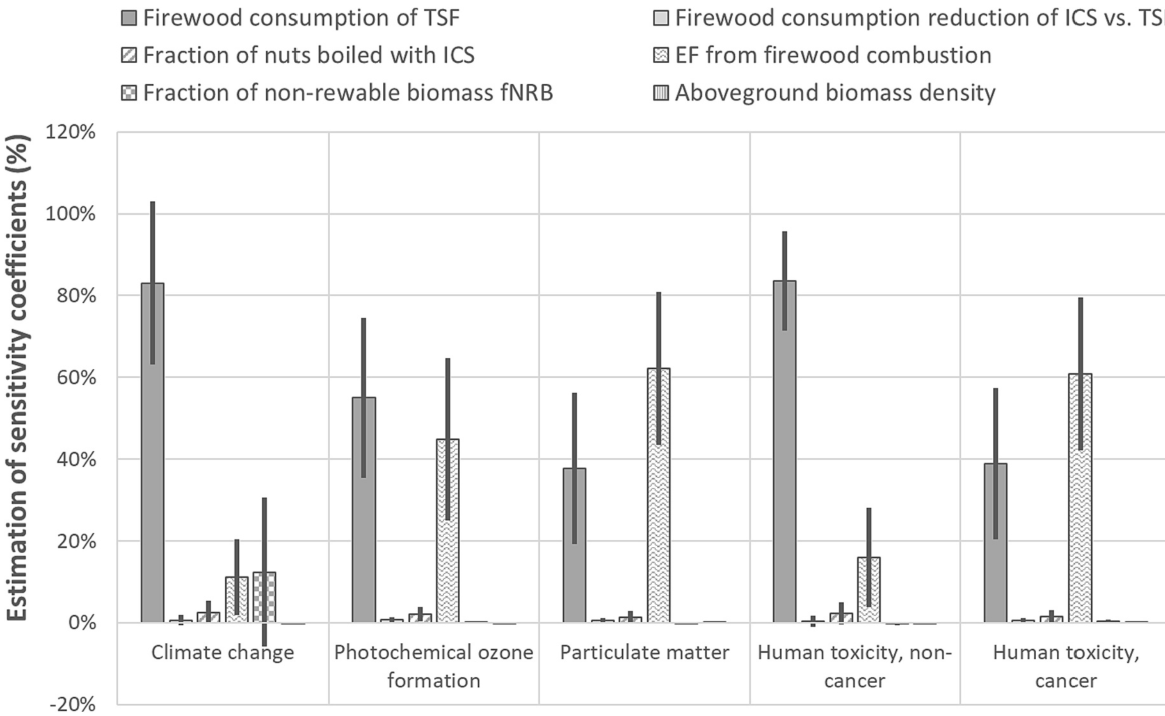

Fig. 8. Minimum (ABO approach), maximum (OAT approach) and mean estimations of sensitivity coefficients of the input parameters related to firewood use accounting.

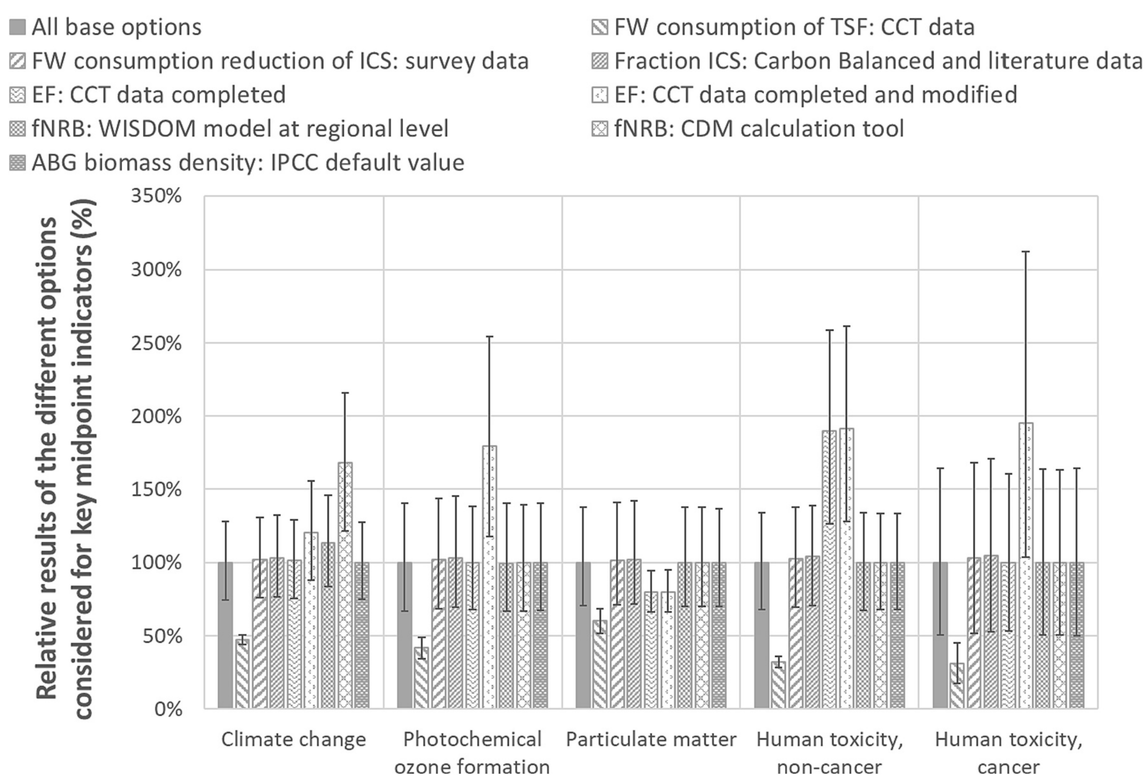

Fig. 9. Results of the sensitivity analyses for key midpoint indicators, relative to the median base results.

confidence interval, and much greater for human toxicity related to non-carcinogenic effects, with a 90% increase in the median and a 101% increase in the confidence interval. When CCT data were also used to extrapolate the emission of other substances, no significant additional effect was observed for the latter two indicators, but effects appeared on the other three: 20% and 27% increases in the median and the confidence interval for climate change, 79% and 87% for photochemical ozone formation, and 95% and 84% for human toxicity related to carcinogenic effects. The main substances involved in these effects were: CH_4 for climate change, ethene for photochemical ozone formation, PM for particulate matter, CO for non-carcinogenic human toxicity, and benzo(*a*)pyrene for carcinogenic human toxicity.

Finally, switching models to estimate fNRB only had an effect on the climate change indicator, with increases of the median results and the range of the 90% confidence interval by 13% and 17%, respectively, when moving from a national to a regional level for the WISDOM model, and by 68% and 77% when switching from the national WISDOM model to the default value from the CDM calculation tool.

4. Discussion

4.1. Environmental impacts and opportunities for improving shea butter production

Despite some disparities in the results from available environmental assessments in the literature (see Supplementary Material B), the LCA results from this case study in section 3.1 confirmed the key role of firewood consumption for nut boiling in most of the key environmental issues of the system studied. Any solution that helps to reduce this consumption is therefore an interesting opportunity for mitigating the environmental impacts of shea butter production.

In this respect, the most widespread measure is ICS design and dissemination (Hafner et al., 2020; UNEP and African Union, 2019; Urmee and Gyamfi, 2014). The environmental benefits of this approach were confirmed in this study, with reported reductions in key midpoint indicators when switching from TSF to ICS of 60% for climate change, 68% for photochemical ozone formation, 40% for particulate matter, and 86% and 90% for human toxicity related, respectively, to non-carcinogenic and carcinogenic effects (see Supplementary Material F). These benefits were found to be significant compared to the uncertainties surrounding the relative performances of TSF and ICS, with a statistical risk that TSF ultimately had a lesser impact than ICS of under 0.02% for all key indicators in the base case, 6.1% for carcinogenic human toxicity and less than 0.7% for all other key indicators when using CCT data completed by laboratory data, and 10.0% for carcinogenic human toxicity and under 2.3% for all other key indicators when using CCT data completed by modified laboratory data (see Supplementary Material F).

Nevertheless, while there is little discussion on the technical benefits of ICS, their adoption by populations using TSF is an important concern and may prove to be limited due to a combination of several barriers, such as low income, a low level of education, or low costs or even free firewood (Urmee and Gyamfi, 2014; Vigolo et al., 2018). As a result, it is essential to consider other strategies for saving firewood, one of which is switching from firewood to another biomass sources. In this regard, using shea nut shells can be attractive in a circular economy approach (Noumi et al., 2013). Indeed, the quantities of shea nut shells obtained after shelling could replace much, if not all, of the firewood used for the boiling operation. However, this would mean adapting the cookstoves to ensure proper combustion of the shells. On the other hand, shea nut shelling is chronologically carried out in the village after the food harvesting season, when women are no longer busy working in the fields, while boiling occurs during the harvesting season. Consequently, shea nut shells are available long after the boiling operation has been completed. The use of shea nut shells as a substitute for firewood therefore implies the establishment of a whole set of logistics to conserve the shells produced from one year to the next if boiling is involved. These logistical issues can be simplified if shea nut shells are used for other purposes, but developing a suitable cookstove is still a challenge. Experiments have to be undertaken to test the feasibility of these options in the field.

This study also showed that there is room for improvement in boiling practices. Indeed, the CCT data for firewood consumption from the Carbon Balanced program was found to be three times lower than field measurements (see Table 2), leading to significant differences in LCA results (see section 3.3). Although there is not enough information available on field measurements to explore and confirm the causes of this difference in consumption, a reasonable guess is that this could be related to the filling of boiling pots, expressed by the mass of nuts boiled per volume of water. Beyond the physical logic, the few data available in the literature tend to confirm this assumption with reported pot fillings of 0.8 to 2.0 kg/l (Gueye, 2011; Noumi, 2010), compared to 3.6 kg/l for CCT. Understanding the causes of these underfills is key in determining the actual potential for impact reduction through improved practices. In particular, as boiling has to be done shortly after harvesting to avoid the degradation of fatty substances, filling rates could depend on harvesting constraints.

Finally, regarding fossil resource use, 74% of the system impact came from shea butter production and refining. This particularly included electricity consumption from the national grid during butter production and natural gas consumption during butter refining. For butter production, an extension of existing PV areas or the installation of a combined heat and power system to supplement the existing boiler using shea cakes could reduce electricity consumption from the grid. For butter refining, setting up an anaerobic digestion system of waste water and bleaching earths would be an interesting solution.

4.2. Towards better accounting of firewood in LCA

Based on a shea butter case study, this work showed that data scarcity is a key challenge for LCA uncertainties related to firewood accounting. In particular, case-specific data, such as firewood consumption for shea nut boiling, were the largest contributor to uncertainties in the climate change indicator in this work, and one of the first two contributors for the other key indicators. The strategy adopted for this case study to overcome the lack of data was to expand the scope for data collection, either by expanding the geographical coverage, or using indirect measurements. However, this approach should be undertaken with extreme caution, as such an expansion can introduce major biases in LCI and ultimately in LCA results. For instance, diverting comparative data, such as CCT data, to estimate the absolute performances of TSF has proved to induce a major deviation of LCA results, much larger than the inherent uncertainties of field measurements.

Despite a larger number of available data or replications, generic data, such as laboratory EF data for firewood combustion, are also a major contributor to LCA uncertainties, especially for key indicators other than climate change, such as particulate matter or carcinogenic human toxicity. But beyond these uncertainties, due in particular to measurement techniques and the variability of biomass composition, the key issue when estimating EF is the suitability of laboratory measurements to represent actual stove performance (Bilsback et al., 2018; Lombardi et al., 2017; Zhang et al., 2017). Indeed, due to the cumbersome nature of EF field measurements and the number of substances involved, choosing an EF dataset for LCA purposes often comes down to choosing between the completeness of laboratory measurements and the field-accuracy of site measurements. One of the strategies explored here to combine the advantages of both data sources was to use field data for available substances and to extrapolate EF from laboratory data for other substances, based on the observed differences between both sources for common substances. Although this approach introduced new uncertainties related to data extrapolation, they might be less than those related to the use of incomplete or non-representative data. Moreover, this approach made it possible to identify the main substances missing from field measurements: methane, ethene, and benzo(*a*)pyrene. Therefore, new field measurement campaigns should focus on adding these substances for their environmental relevance, mainly methane, given their importance for climate change and the technical feasibility of their measurement. Indeed, specific infrared methane and COV portable analyzers are available on the market. Combustion smoke analyzers can also quantify the total amount of light hydrocarbons (C_xH_y) whose main compound is methane.

In addition to these data challenges, firewood accounting in LCA also suffers from methodology issues, especially in the determination of fNRB, which is a key parameter for climate change. Bailis et al. (2017) found that fNRB estimates could be very different between the WISDOM model and the CDM calculation tool. The results of this work also showed in Burkina Faso that uncertainties related to the choice between the two models were greater than the intrinsic uncertainties of the WISDOM model, including both calculation uncertainties and the choice between national or regional levels. Since the WISDOM model includes the best available knowledge on firewood supply and demand and provides factors for 88 countries and 1482 sub-national levels (Bailis et al., 2015), its use can be recommended for LCA purposes.

5. Conclusions

Based on current best practices for firewood inclusion in LCA, this work proposes an exhaustive framework for LCI modeling, combined with a configurable dataset for other studies (Benoist et al., 2023). The case study considered on shea butter production proved the usability of this framework, while producing an original LCA, based on primary data from a mechanized production unit in Bobo-Dioulasso, Burkina Faso, and a refining unit in St-Léonard, France. The LCA results obtained confirmed the key role of firewood use for most midpoint categories.

A deeper analysis of firewood accounting, through uncertainty and sensitivity analyses, showed that the critical parameters for the final results were data collection for firewood consumption and EF, and the method selected for estimating fNRB. While the most effective strategies for collecting case-specific data must be defined on an ad hoc basis, the work undertaken made it possible to recommend preferential use of field data for EF determination, even if it means completing and extrapolating certain factors from laboratory data, and preferential use of the WISDOM model for fNRB estimation.

However, these conclusions are limited by the fact that only one case study was covered in this work. Applying the proposed framework to other value chains would be useful for checking the genericity of both the framework and the critical parameters identified. Improvements could also be introduced to the framework to reduce uncertainties in the results without unduly complicating the modeling process or data collection. For instance, introducing parameters on wood moisture or forest species could help to adapt generic EF from the literature to specific cases and reduce the corresponding uncertainties.

For the shea butter production in particular, reducing firewood consumption is a key driver for tackling several environmental issues of the value chain. The dissemination of ICS is currently the most widespread solution for such a reduction, despite sometimes limited results. In this work, other promising options were identified, such as the substitution of firewood by alternate biomass sources, such as shea nutshells, and improved boiling practices, especially as regards pot filling.

Author statement

The authors declare that they did not use generative artificial intelligence (AI) and AI-assisted technologies in the writing process, apart from basic tools for checking English grammar.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Some of the co-autors are directly involved in the shea butter industry, which is the case study of this work. Especially, Christophe Godard, Hubert Ouedraogo, and Marjorie Riesgo Saives, from OLVEA group, worked in the shea butter production sector at the time of publication. Patricia Martz and Stéphanie Ringeissen, from L'Oréal R&I, worked in the cosmetics sector at the time of publication. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used for this publication is available in the Supplementary Material.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2024.107414.

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