International Journal of Environmental Science and Technology (2023) 20:9311–9334
https://doi.org/10.1007/s13762-022-04752-1

REVIEW

A systematic review of densified biomass products life cycle assessments

L. Esquiaqui[1] · **S. D. F. de Oliveira Miranda Santos**[2] · **C. M. L. Ugaya**[2]

Received: 14 May 2022 / Revised: 21 November 2022 / Accepted: 30 December 2022 / Published online: 10 January 2023

Abstract

A systematic review of the state of the art of LCA biomass densification for energy purposes has been conducted. The aspects analyzed in the studies were: the temporal and geographical scope; type of raw material; densification technology, function, and functional unit; system boundary; allocation approach; impact assessment method; impact categories; sensitivity analysis; and uncertainty. Finally, a process contribution analysis with the environmental impacts is provided. Based on the results, wood fuels correspond to 56% of the biomass analyzed. The pelletizing technology represents 79% of the studies. A significant percentage of the life cycle assessments (88%) explicitly state the functional unit; however, 12% of these studies do not present it straightforwardly. Different functional units are used in the analyzed studies, with one MegaJoule (1 MJ) being the most common (in 33% of the studies). The most commonly used approach was from Cradle-to-grave, representing 54% of the studies. In this review, 54% of the studies applied allocation, 27% mass allocation, 17% market value allocation, and 4% combined. The typically employed life cycle impact assessment methods in the revised studies were ReCiPe, CML, and IPCC, representing 23, 21, and 19%, respectively. The most frequent impact categories among the studies are global warming (96.15%), acidification (58%), eutrophication (50%), ozone depletion (46%), and photochemical ozone formation (42%). The critical point most highlighted in the studies is the densification process, dominated by the use of machines, usually with high energy consumption, resulting in emissions of CO_2 and CH_4.

Keywords Briquetting · Pelleting · Energy · Environmental impact · Sustainability

Introduction

Last decades faced a growing need for alternative fuels to those derived from fossil sources to reduce environmental impact and ensure technical and economically feasible energy options (Frankfurt School – UNEP 2019). When there is no land transformation, these fuels may reduce greenhouse gas (GHG) emissions and are consequently crucial for environmental conservation. One of the available energy sources is biomass, given that it has become a modern energy vector resulting from the development of efficient conversion technologies, such as gasification and pyrolysis (Nogueira 2003). Besides, biomass plays a fundamental role due to its inclusion in countries' climate policies that directly or indirectly encourage renewable energy.

Ireland, for example, has implemented a scheme to support heat generation from renewable material, installation, and continued use of biomass (Bioenergy International 2019). China has incorporated programs to implement domestic biogas systems in rural areas as a traditional biomass energy strategy (Zheng et al. 2020). Brazil puts into practice the program "Sustainable Steelmaking—production of charcoal based on sustainable renewable biomass for the steel industry in Brazil," implemented in Minas Gerais state in 2018, to mitigate GHG emissions. One of the most outstanding results of this project is the average reduction of GHG emissions of 1415 kg CO_2eq/t charcoal, five times more when compared to the project goal, which was 270 kg CO_2eq/t charcoal (GEF and UNDP 2019). Ghana

---

Editorial responsibility: Parveen Fatemeh Rupani.

✉ L. Esquiaqui
luisesquiaquimarin@gmail.com

[1] Postgraduate Program in Environmental Science and Technology, The Federal University of Technology – Paraná, Curitiba, Paraná 81280-340, Brazil

[2] The Federal University of Technology – Paraná, R. Deputado Heitor Alencar Furtado, 5.000, Curitiba, Paraná 81280-340, Brazil

has proposed increased use of renewable energy for bioelectricity generation, for example, to purchase and build small-scale biomass briquetting and pelletizing machines for domestic and export use (MoEn 2019). Other countries are also trying to increase the share of renewable energy from the clean and efficient conversion of renewable biomass resources (REN21 2019, p. 21).

The progressive substitution of fossil fuels by renewable sources has changed the energy matrix of countries such as Brazil, Switzerland, China, and Canada, which approach forest biomass as one of the aspects of agro-energy policy guidelines. For this reason, biofuel production is expected to triple over the next three decades (Cloete 2019). One of the possibilities is to use forest residues as an energy source through densification to create high-added value and energy-efficient products.

Because of the increasing demand for forest residues as an energy source, it is essential to improve the analysis of environmental impacts to promote new technology development. Life cycle assessments (LCA) of densified products are already available, and most focus on the densification of agro-industrial residues and lignocellulosic materials (Bajwa et al. 2018). Saba et al. (2020) demonstrated that the environmental effects of olive straw briquettes are lower than diesel. Wang et al. (2017) compared LCA between corn straw briquettes and charcoal in China, showing that the former is more ecological. Benetto et al. (2015) studied heat production from grape marc pellets and conventional fuels, employing a comparative LCA based on primary data. The authors found that pellets reduce climate change. Rousset et al. (2011) analyzed the environmental impact of charcoal briquettes made from eucalyptus wood with starch as a binding agent. The study used global warming potential (GWP), verifying that the energy supply of 1 kg of briquettes sequestered 3.9690 kg of CO_2. These results indicate how CO_2 emissions throughout the production process are compensated by the environmental quality of charcoal from eucalyptus and babassu fruit starch plantations.

The last ten years have seen many LCA studies of biomass-densified products. However, little attention has been given to reviewing differences regarding objective and scope, method, and data uncertainties. Therefore, the current review aims to provide state of the art in using LCA to examine the impacts of biomass densification. Above all, information regarding the highest contributing processes in different impact categories of Cradle-to-gate and Cradle-to-grave approaches identified in the studies stands out. The results of this review are helpful for professionals working with biomass producers in research and development (R&D), product certification, and decision making regarding public policies of renewable energy markets.

Materials and methods

To achieve the proposed objective, a systematic review was conducted to identify relevant articles on biomass densification and LCA. To this end, the Scopus and Google Scholar platforms were used, limiting publications between 2010 and 2020 regarding the environmental effect of briquettes and biomass resource processing technologies used to produce energy. We identified that before 2010 there was a shortage of articles describing in detail the analysis of results for identifying critical points in densification processes. The search sequences were applied to the title, abstract, and keywords, as presented in Table 1.

The search resulted in 85 articles of interest. The technique known as "snowballing" was used to include 28 articles by reading the references of the articles. A snowball involves deepening a specific search by evaluating studies related to the topic that was not previously identified, intending to reveal more potential articles. LCAs were selected following two criteria: (1) was there an evaluation of the environmental impacts of biomass used for energy purposes? (2) were the critical points (Hotspots) that most contribute to environmental impacts presented?

Afterward reading the paper, 61 articles were disregarded because there was not enough detail in the analysis and explanation of the environmental impact of the process's critical points (For example, papers that do not include the cut-off criteria or do not present LCA results, or publications with subjects different from the scope of this study). This left 52 publications to be assessed (see "Appendix A"). The publications were analyzed based on the evaluating and reporting LCA data analysis aspects listed in Zumsteg

Table 1 Keyword used to search articles on the Scopus platform

Topic	Search algorithm
Specific keywords for environmental impacts	("Life cycle assessment" OR "LCA" OR "environmental impacts")
Specific keywords for densification technology	AND ("Briquetting" OR "pelleting" OR "densification")
Specific keywords for the type of biomass used	AND ("biomass" OR "Charcoal fines" OR "charcoal dust" OR "charcoal" OR "wood" OR "Woody" OR "lignocellulosic" OR "densified" OR "logging residues" OR "Cellulosic" OR "agricultural residue" OR "pellet")

et al. (2012) and (ISO 2006a), and ISO (2006b). The specific points analyzed in each work are presented in Table 2.

Results and discussion

Biomass densification unit process

Densification processes involve several phases, including biomass feedstock pre-treatment, densification, and post-treatment (Fig. 1). Pre-treatment stages vary greatly depending on the raw material qualities. They often include size reduction, drying, and conditioning. The densification products are transported into a cooler and filtered to eliminate tiny particles after densification (Stelte et al. 2012).

The unit processes of dendroenergetic biomass are presented below, from harvesting raw material to storing the briquettes or pellets. The following describes a Gate-to-gate approach to the typical biomass densification process.

1. Storage of raw and densified biomass: densifiable biomass requires a large area and specific infrastructure (silos and warehouses) for the temporary storage of the material and to reduce the risk of microbiological damage. This last aspect is vital since these microbial actions can compromise the calorific value of the product, significantly reducing its usefulness (Muazu et al. 2017). To keep them in proper condition without risk of degradation, it is necessary to use mechanical means of drying (fans and heaters). This equipment can increase energy consumption, which could have significant environmental effects (Fantozzi and Buratti 2010).
2. Pre-treatment of biomass: The biomass used generally has considerable moisture content and does not have a uniform size. It is, therefore, necessary to implement additional operations such as drying, crushing, and grinding.

In the compaction of biomass, the moisture content is an essential variable, because its excess can lead to decreased calorific power of briquettes or pellets, in addition to operational problems such as clogging in the equipment (Donato et al. 2015). According to some studies, the ideal moisture content range is between 5 and 10% (Brugnera 2016; De Fontes et al. 1989; Donato et al. 2015). However, this percentage depends on the initial and final water content and biomass characteristics. Sometimes the raw material can be collected with a humidity suitable for compaction, such as coffee or corn straw. In the case of sugarcane bagasse, grass, and firewood, drying is essential to provide evidence of some benefit to the process (Nogueira 2003). Some alternatives used for biomass drying are sun drying, combus-

Table 2 Topics covered and analysis of publications.

Topics	Analysis
General information	
Geographical context	In what regional context was the study prepared?
Publication year	What was the year of publication of the study?
Objective and scope	
Raw material	Which raw material was used?
Densification technology	Which densification technology has been applied?
Function and functional unit	Which functional unit was applied?
	Were functional units declared explicitly or implicitly?
Life cycle inventory	
System boundary	What processes were included in the system boundary?
Allocation	Which allocation method was applied?
Biogenic carbon	Was the biogenic carbon considered in the study?
Life cycle impact assessment	
Compatible with ISO 14040/14044	Was the ISO 14040/14044 considered in the study?
LCIA method	What method of the LCIA was applied?
Impact category(s)	Which impact category(ies) was/were evaluated?
Life cycle interpretation	
Sensitivity analysis	Were additional scenarios considered?
Uncertainty	What is the model used to represent the uncertainties in the analyzed study?
Hotspots	Was there an identification of critical processes in each impact category?

Source: Adapted from Muench and Guenther (2013)

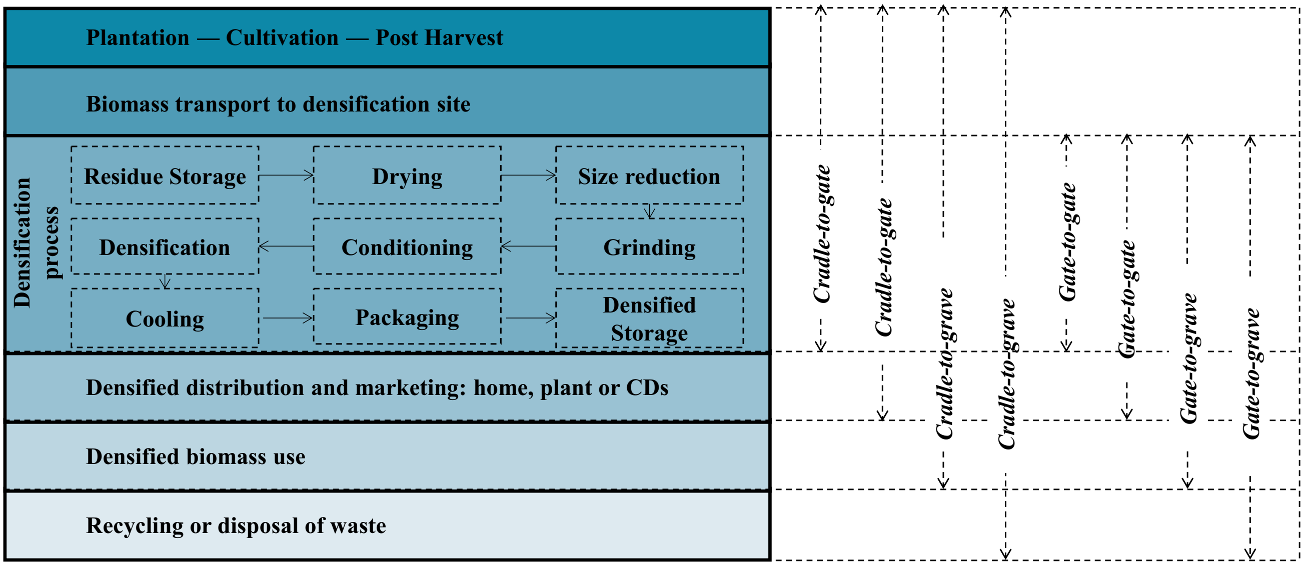


Fig. 1 A typical Cradle-to-grave approach to the biomass densification process

tion gases from the preheating of thermal fluid, rotary kilns, drying in greenhouses, and flash dryers, among others (Dias et al. 2012). The drying speed depends on temperature, relative humidity, airflow, exposure time, and the material's physical–chemical properties (Rendeiro et al. 2008). Consequently, achieving the ideal moisture content can lead to considerable energy consumption (Li et al. 2012). Adams et al. (2015) evaluated the environmental impacts of integrating the roasting process into the bioenergy supply chain. The authors determined that the impact on pellet production depends heavily on the biomass drying requirement.

The biomass size reduction is usually made through a chopper/crusher, hammer mill, knife, or ball mill (De Fontes et al. 1989). This stage is critical to ensure that the particle size is compatible with the compaction equipment, in addition to promoting faster drying and improving the density and strength of the final product (Rendeiro et al. 2008). The result of the crushing is usually tiny particles of the original raw material (close to the powder or pieces of a few centimeters). The energy required and the impacts associated with grinding depend on the desired particle size and the nature of the biomass to be processed (Bajwa et al. 2018; Tabata and Okuda 2012).

Usually, the conditioning takes place in two substages. The first is the sifting of the raw material, which is essential in the biomass densification process to separate the material into two or more fractions with particles of different sizes and avoid contamination of the material of interest (Bajwa et al. 2018). This is performed using metallic vibrating screens of different sizes and shapes according to the type of material to be sieved (De Fontes et al. 1989). The second substage is the pre-heating of biomass, in which the material's feeding temperature is high, activating natural binders, for example, lignin, or those added as binders in the process, such as starch or even vegetal tar (Nogueira 2003). This way, obtaining a denser and more resistant final product is possible. This operation usually involves friction, fluidized bed heating, steam conditioning with electrical resistance, or heat exchangers with thermal oil (Dias et al. 2012). The energy required and the impacts associated with it can be favored by the drop in energy needed to process each kilogram of briquette or pellets because the pre-heating results in the decrease of the necessary pressure by the deformation of thermoplastic particles, especially in the case of the use of extruder screws (Bajwa et al. 2018; De Fontes et al. 1989; Dias et al. 2012).

3. Densification: compaction is one of the most important stages to produce pellets and briquettes (Bajwa et al. 2018). Quirino and Brito (1991) define the process as the way to concentrate the available energy in the biomass that, when compacted, generates solid agglomerates called briquettes or pellets. The pellets usually have a smaller dimension and are generally manufactured by extrusion, whereas the briquettes have a larger size because they are produced by compaction (Dias et al. 2012). Generally, the most used equipment in this phase is the pellet press, briquette press, mechanical piston press, hydraulic piston press, roller press, extruder screw press, conical screw press, press with cylindrical screw and heated die, and double screw press (Bajwa

et al. 2018; Muazu et al. 2017). This type of equipment consumes a considerable amount of energy due to the energy requirements needed for extrusion or compaction. This unitary operation can sometimes be performed manually (Njenga et al. 2014). It can be observed that the choice of densification technology plays an important role. However, the compaction requirement according to the nature of the biomass must be evaluated (Muazu et al. 2017).

4. Cooling: the densified material usually suffers an increase in temperature due to the heating resulting from shearing between the particles (surface temperature above 200 °C) (Dias et al. 2012). Therefore, it is essential to cool the final product to avoid accidents, pack it properly, and facilitate its subsequent transportation to the storage area (Nogueira 2003). Cooling is generally done at room temperature, although other alternatives are also used, such as a box dryer and/or a counterflow chiller (Bajwa et al. 2018; Li et al. 2012). The adaptation of this operation requires a specific area besides energy to ensure drying or cooling (Muazu et al. 2017).
5. Packaging: according to the final product usage, packaging must be considered to prevent losses from exposure to bad weather and promote handling, transport, and distribution (DIAS et al. 2012). This scenario is valid for use of briquettes or pellets for domestic or local applications. Nevertheless, for large-scale thermal conversion, it should be transported and distributed in bulk (Muazu et al. 2017). The packaging operation can occur manually or through industrial sewing machines as an alternative to replacing seams by hand. These types of equipment generally have low energy consumption (Dias et al. 2012).

The system boundary for each study in this review can be found in “Appendix A”.

General information

Publication year

In the period under analysis, an initial LCA study applying the attributional approach was conducted by Fantozzi and Buratti (2010). They led an assessment of the environmental impact of using wood pellets for thermal energy production. They reported that the most significant difficulty in the study was the availability of data on the pelletizing process since only some data on the various phases of the process were available in the literature regarding the number of publications related to the LCA of biomass densification. Figure 2 shows there are still very few scientific publications during the period, peaking in 2015 with ten papers published.

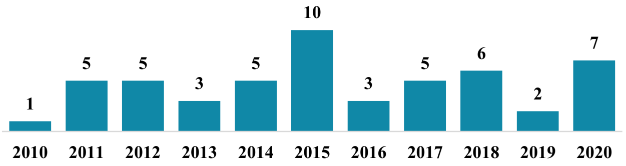


Fig. 2 Number of articles according to publication’s year

Geographical context

Another relevant aspect to consider is the geographical scope of the studies. Figure 3 shows that 46.15% of biomass densification LCA for energy purposes were in a European context, from which Italy represented 33.3%, Sweden and Portugal, 12.5% for both. These results can be explained by Europe's emphasis on harnessing biomass for energy purposes, probably based on European Union (EU) policies on renewable fuels and bioenergy, environmental protection, climate change, and clean energy (Burck et al. 2019; Cabuzel 2019). America is represented with 30.43%, with the USA and Canada accounting for 50.0% and 33.3%, respectively. There is a similarity among European, American, and Asian LCAs concerning briquettes or pellets, where 32 of 52 studies (61.5%) report biomass consumption for heat production. Other regions represent the remaining percentage.

Objective and scope

Compatibility with ISO 14040/14044

The International Organization for Standardization developed two complementary standards to assure the rigor, transparency, and sound methodology of life cycle assessments: ISO 14040 describes the concepts and structure of life cycle assessments (ISO 2006a), while ISO 14044 specifies four phases: the definition of the goal and the scope of the study, the preparation of a life cycle inventory (an inventory of inputs and outputs), the impact assessment, and finally the interpretation (ISO 2006b). In this review, 69.23% of the studies followed these guidelines. For example, Clare et al. (2015), Porsö et al. (2018), and Ruhul Kabir and Kumar (2012) explicitly mentioned having applied it. On the other hand, The European Commission Joint Research Centre established the International Reference Life Cycle Data System (ILCD) manual, which provides technical recommendations for undertaking extensive LCA assessments. It includes precise definitions and standards to restrict decision freedom and enhance the uniformity of LCA findings and quality assurance, and adheres to the ISO 14040 and 14044 LCA requirements. Kylili et al. (2016) employed the recommendations from ILCD to the studies.

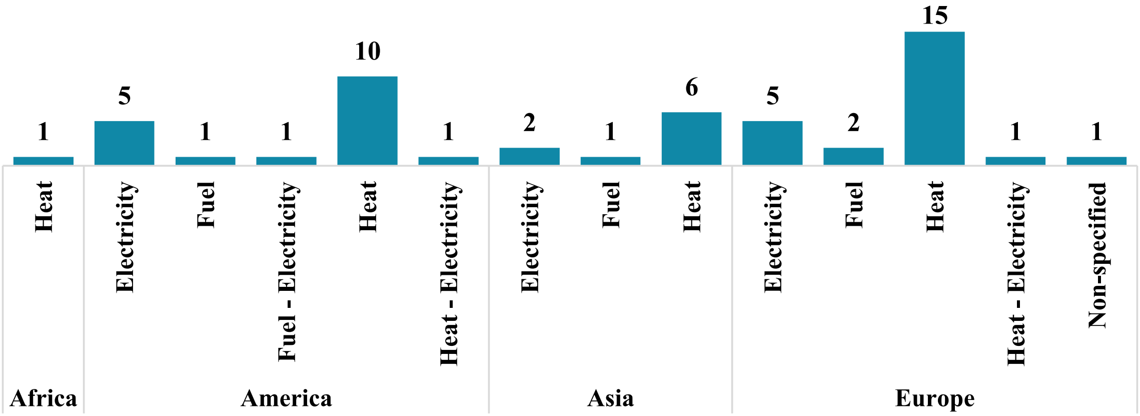


Fig. 3 Studies geographical distribution and main functions

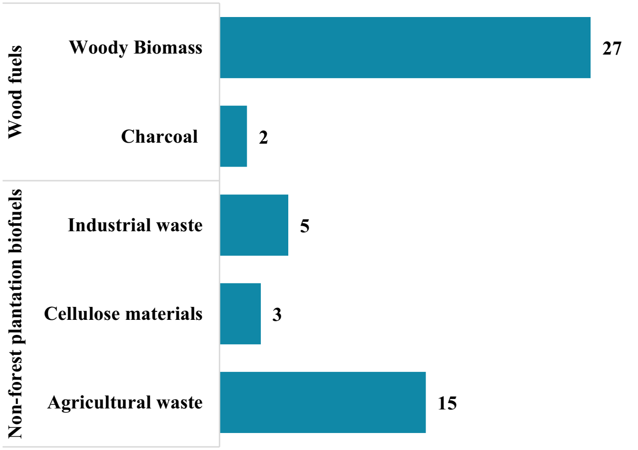


Fig. 4 Types of biomass raw materials considered in the studies

Raw material

The energy sources of biomass included in LCA can be classified into biofuels from wood (dendrofuels), non-forest plantation biofuels (agrofuels), and urban waste biofuels (Nogueira 2003).

Wood fuels correspond to 55.76% of studies, with 27 and 2 studies on woody biomass and charcoal, respectively. Non-wood plantation fuels represent 44.23% of publications. Agricultural waste was the majority in 15 studies, followed by industrial waste in five studies and, finally, cellulose materials in 3 studies. Notably, agricultural and lignocellulosic materials have been heavily represented in LCA studies. Nowadays, agricultural and lignocellulosic biomass are widely used in the biobased economy. This can be partly explained by public policies adopted by some countries to create value from biomass waste through new technologies, processes, and sustainable products (Burck et al. 2019; Harvey et al. 2019; Speranza et al. 2017). Figure 4 shows this classification for the studies analyzed.

Densification technology

Other significant advantages of biomass densification are reduction in moisture content through drying (Chaisuwan et al. 2020; Hu et al. 2014; Saba et al. 2020; Wang et al. 2017); in some cases, increased calorific value (Brugnera 2016; Rodriguez et al. 2017); higher yield in use and reduction in volatile content (Donato et al. 2015). This type of product has an essential influence on the environment. For example, Li et al. (2012) evaluated different fuel impacts: coal, natural gas, wood pellets, and light fuel oil. The authors point out that wood pellets have lower CO_2 eq emissions when used as fuel in the drying process, presenting a considerable drop of 45%, 28%, and 22% compared to coal, light fuel oil, and natural gas, respectively.

All these advantages have been conferred throughout several studies of LCA of briquetting and pelletization of biomass. The studies do not include other possible conversion routes, such as fermentation, liquefaction, direct combustion, pyrolysis, gasification, biodigestion, cracking, and esterification. Pelletization, briquetting, and other processes (manual and combined operations) account for 78.85, 17.31, and 3.84% of total studies, respectively. The pelletizing LCAs have a strong focus on lignocellulosic biomass. This biomass type is equivalent to 63.41% woody biomass as a raw material in the pelletization technology.

Function and functional unit

Functional unit (FU) objective is to quantify the identified functions and ensure the comparability of LCA results on a common basis when evaluated in different processes or scenarios (ISO 2006a; Kylili et al. 2016; Rajabi Hamedani et al. 2019). In this review, the main functions of the evaluated product systems were electricity generation and heat generation, as presented in Fig. 3.

A large proportion of LCA (88.46%) explicitly declares FU; however, some studies (11.54%) present FU implicitly through data in figure captions rather than explicitly. In this review, it was possible to notice that the measurability and precise definition of FU continue to be a problem. Such as in the reviews of the following authors: Muazu et al. (2017); Muench and Guenther (2013); these limitations are also pointed out in the works on biomass densification and bioenergy, respectively. They point out that the FUs defined in the biomass energy LCA are not uniform. For example, Manandhar and Shah (2017) described the functional unit as one metric ton (t) of dry biomass at 0% moisture delivered to the door of the biorefinery, while Porsö et al. (2018) defined the functional unit as 1 GJ of fuel (produced in one year). This represents a significant challenge when comparing different systems.

Figure 5 shows the different FUs used in the analyzed studies, with one megaJoule (1 MJ) covering 32.64% of studies, the most common in the literature. Recent literature has identified a fundamental problem associated with selecting functional units in comparative studies. Benetto et al. (2015) ensure that using a mass FU, for example, 1 ton of pellets, can be consistent, although the authors conclude that in comparative LCA studies between energy scenarios, an adequate FU is the production of 1 MJ of energy since it is aligned to the product's function (Fantozzi and Buratti 2010; Sultana and Kumar 2011; Vera et al. 2020).

Life cycle inventory

System boundary

In general terms, biomass compaction is similar, with many common unit processes, which vary depending on the raw material's physical–chemical properties (Dias et al. 2012). In Fig. 6, there is a view of biomass compaction system life cycle stages.

Figure 6 shows the kinds of system boundaries for biomass densification LCAs in the literature. It can be observed that 53.84% of studies evaluated the environmental impacts of the whole biomass densification process (Cradle-to-grave). These studies assessed biomass extraction and harvest and, in some cases, included biomass transportation from forest to densification plant and the use and disposal (ash and packaging). It has been the most common approach. Conversely, the Cradle-to-gate process represented 36.53%, considering biomass extraction to briquettes or pellets production units. In this case, the use and disposal phases were ignored. The availability of data to assess the impact of waste is limited, which may cause biased results. The Gate-to-gate evaluation reached 5.76%. In these studies, partial analyses of different unit processes were performed. Not all

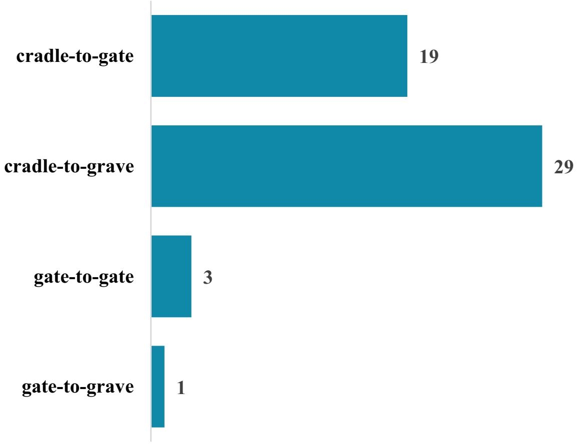
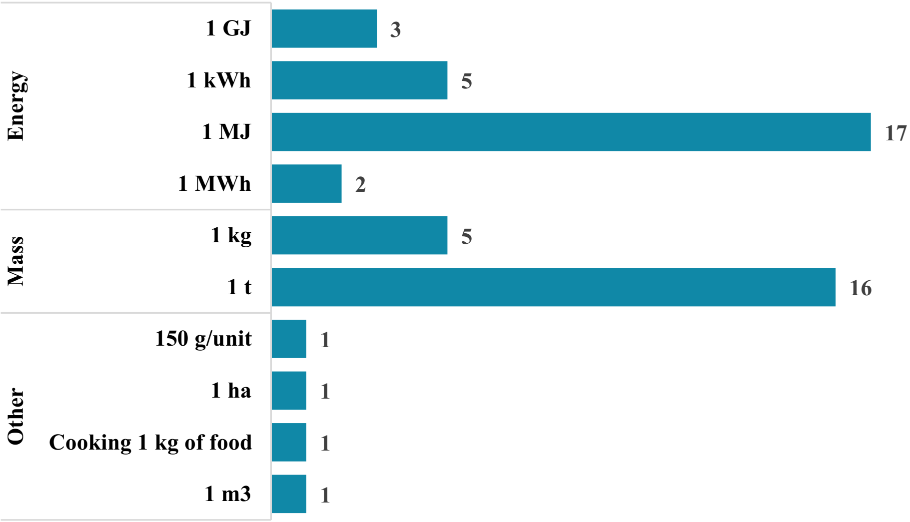


Fig. 6 Percentage distribution of LCA variants analyzed in the evaluated studies

Fig. 5 Functional unit considered in the studies evaluated



densification goes through all these processes, as it depends on the type and format of the raw material.

Another evaluation scenario found in the literature was from cradle-to-cradle. It is a specific type of evaluation from the cradle to the grave. For example, Villabona and Kafarov (2018) evaluated six stages: transport, drying, crushing, compaction, and biomass combustion. Afterward, they merged these as one processes with the simultaneous adoption of the cradle-to-cradle technique in the LCA, although they do not provide further details.

There are standard stages of biomass densification in the Gate-to-gate variant. However, many studies approach these unit processes as a black box. Avoiding the "black box" ensures data accuracy, reduces uncertainty, provides a reasonable process mapping, and avoids multifunctionality problems (JRC 2011).

Capital goods

The number of studies considering capital goods, such as construction and machinery (infrastructure), was reduced due to their complexity (Benetto et al. 2015; Rousset et al. 2011; Tsalidis et al. 2014; Wang et al. 2017). Silva et al. (2018) did an LCA study of some construction products, with and without infrastructure, using Monte Carlo's analysis to calculate uncertainty caused by capital goods flows. The authors identified a high uncertainty, although they point out that it is a limited area of opportunity since changing capital goods is difficult due to the investments required, besides the effort to collect data from these flows. Ugaya et al. (2020) corroborate this statement in the organizational life cycle at the Center for Sustainability Life Cycle Assessment. The authors identify that once the installation is there, there are no management improvements that could be made related to construction. This trend was observed in the evaluated studies, as 42.31% excluded environmental impacts from capital goods and infrastructure and included only operational processes. 38.46% of the papers covered such information, aiming at a complete analysis of environmental impacts. The remaining 19.23% did not state whether or not they had addressed the building and other capital goods for a biomass densification system.

Allocation

Allocation represents the division of the flows (inbound and/or outbound) of a process or a product system between the product system under study and other product systems, aiming at assigning the environmental impact between these products (Azapagic and Clift 1999; Ekvall and Finnveden 2001). ISO (2006a) suggests avoiding allocation. Usually, the allocation is made in terms of physical properties (such as mass or energy) or economic criteria (such as price) of the products involved.

Several authors discussed the choice of allocation method in the evaluated papers. Li et al. (2012) conducted a sensitivity analysis to compare allocation methods and identify the environmental impact of the pelletization process. The authors determined that wheat straw (a by-product of cereal production) has a low market price. Consequently, when using economic allocation, the environmental load is low compared to mass allocation.

Given this framework, it is essential to note that the choice of allocation method can considerably influence the results of the LCA studies and, consequently, the decision making based on these results (Miranda Santos et al. 2017; Sandin et al. 2015). In this review, 53.84% of the studies dealt with allocation; 26.92% mass allocation; 17.30% market value allocation; and 3.84% combined (the author compared different allocation approaches) and volume, energy, and energy, 1.92% for each one (see Fig. 7). It is interesting to observe that economic allocation was considered, using as a reference the economic price of the market to assign environmental loads to co-products (Bergman et al. 2014; Rajabi Hamedani et al. 2019; Wang et al. 2017). However, Muench and Guenther (2013) indicated that economic allocation should be avoided due to the uncertainties arising from fluctuations in product prices. On the other hand, 9.62% of the studies considered the recommendations of ISO 14044, avoiding allocation and assigning energy consumption and emissions to the densified product. In this case, the authors separated the unit process into additional sub-processes and collected input and output data for these sub-processes. System expansion was considered by Benetto et al. (2015), who studied four approaches: Cut-Off, Mass Allocation, Economic Allocation, and System Expansion to deal with multifunctionality through sensitivity analysis. Finally, 19.23% was not applicable because the raw material was considered a “by-product”. In this case, the environmental impact has

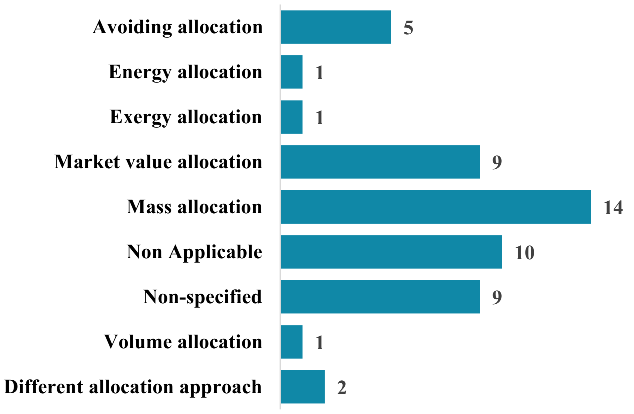


Fig. 7 Allocation considered in the evaluated studies

been assigned to the main product. Finally, 17.30% did not indicate the allocation approach used in the study.

Carbon cycles in biomass densification LCA

Carbon cycles in biomass densification LCA are essential because biomass has been considered one attractive and promising source of dendroenergy, owing to the carbon–neutral assumption. The biogenic CO_2 emissions are eventually absorbed by biomass regrowth via photosynthesis. This assumption is generally accepted in LCA. In this review, 36.54% of the studies considered carbon emissions from biomass utilization as negligible due to the carbon neutral assumption of bioenergy. In this sense, Liu et al. (2018) considered this assumption, carbon neutrality in life cycle assessment, to have several issues, with particular emphasis on possible carbon accounting errors at the product level. The authors concluded that improving the estimation of the climate change impacts of bioenergy use is essential. On the other hand, 36.54% of the study estimated biogenic carbon and removal. These researchers have sought to remedy the related accounting inaccuracies in LCA due to the increased knowledge of carbon emissions caused by altered carbon dynamics. However, uncertainty is inevitable since no widely acknowledged model exists to predict carbon dynamics, focusing on addressing all aspects of the carbon cycle. Finally, 28.85% did not specify how carbon cycles were modeled to produce biomass densification products.

Life cycle impact assessment

LCIA method

In the LCIA phase, characterization methods are relevant because they provide potential environmental impact factors of specific substances, allowing the calculation of an environmental load of each elementary flow (input and/or output) in terms of a common unit of the category indicator.

Midpoint models focus on environmental problems in the middle of the environmental cause and effect chain. At the same time, the endpoint is oriented to damage occurring at the end of the chain.

Lenzen (2006) states that a midpoint approach may favor helpful information to stakeholders because it is less subjective than endpoint methods. However, it is more relevant in decision making when directed to a damage pathway. The reviewed studies used different methods in the LCIA phase, as presented in Fig. 8.

The most used methods in the revised studies were ReCiPe, CML, and IPCC, representing 23.08, 21.15, and 19.23%, respectively. Recipe provides midpoint and endpoint characterization factors. Ecoindicator 99 represented 1.92% of the studies. For example, Benetto et al. (2015) evaluated the environmental impacts from both perspectives, orienting the results to impact. Impact 2002+ was also addressed and reached 7.69%, demonstrating advantages since it can be used in combined approaches, such as ReCiPe. TRACI got 13.46% of the revised studies, focusing mainly on midpoint categories. 7.69% of the evaluated studies did not explicitly state the characterization method implemented, although the figures and results made it possible to identify the LCIA method.

When choosing the method, it is crucial to consider the regionalization of LCIA since each study is from a source under different conditions, which can have a strong influence on the behavior of pollutants and the sensitivity of possible exposed receptors in the studied region (Potting et al. 2006; RAICV 2019).

There are guidance documents available that give advice on models and characterization factors that should be utilized for impact assessment in LCA applications. The following are examples: The Recommendations for Life Cycle

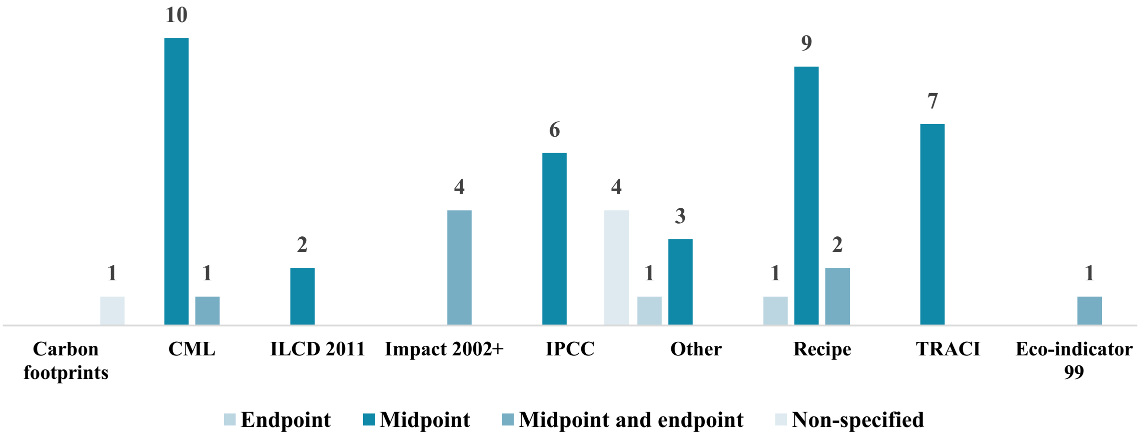


Fig. 8 LCIA methods used in the revised articles

Impact Assessment in the European context (JRC 2011), Global Guidance for Life Cycle Impact Assessment Indicators (Frischknecht and Jolliet 2019), etc.

Impact categories

The LCIA methods have several specific categories. The impact categories considered in the studies can be seen in Fig. 9.

Studies' most frequent impact categories are global warming (96.15% of the studies), acidification (57.69%), eutrophication (50%), ozone depletion (46.15%), and photochemical ozone formation (42.30%).

The choice of impact categories for an LCIA is subjective, usually subject to the objectives and scope of the LCIA method (Cleary 2009). The significant differences in approach are found in the categories used in the analysis: particulate matter formation, organic and inorganic respiration, and energy use are not very popular within densified biomass studies. The difference is that most studies consider the intermediate effects as "midpoints".

The more impact categories are considered, the more complete the study becomes as more environmental mechanisms are evaluated. This particularity allows a holistic assessment (Mayer et al. 2019). To simplify, however, studies such as Rousset et al. (2011) and Njenga et al. (2014) evaluated impacts exclusively associated with the Global Warming Potential of fine charcoal briquettes produced from wood and disregarded other impact categories. In contrast, Saba et al. (2020) emphasized the importance of including several impact categories in the LCA study of bioenergy systems. Therefore, the authors selected an IMPACT 2002+ method because it brings all possible impact categories, highly required by the industry, to midpoint categories (e.g., land occupation, global warming, and ozone depletion) and endpoint categories.

Life cycle interpretation

Analysis of sensitivity/scenarios and uncertainties

The sensitivity and uncertainty analyses are part of the interpretation phase, which are used to improve the study's overall quality, supporting the reliability of the resulting data (JRC 2011). These analyses are rare

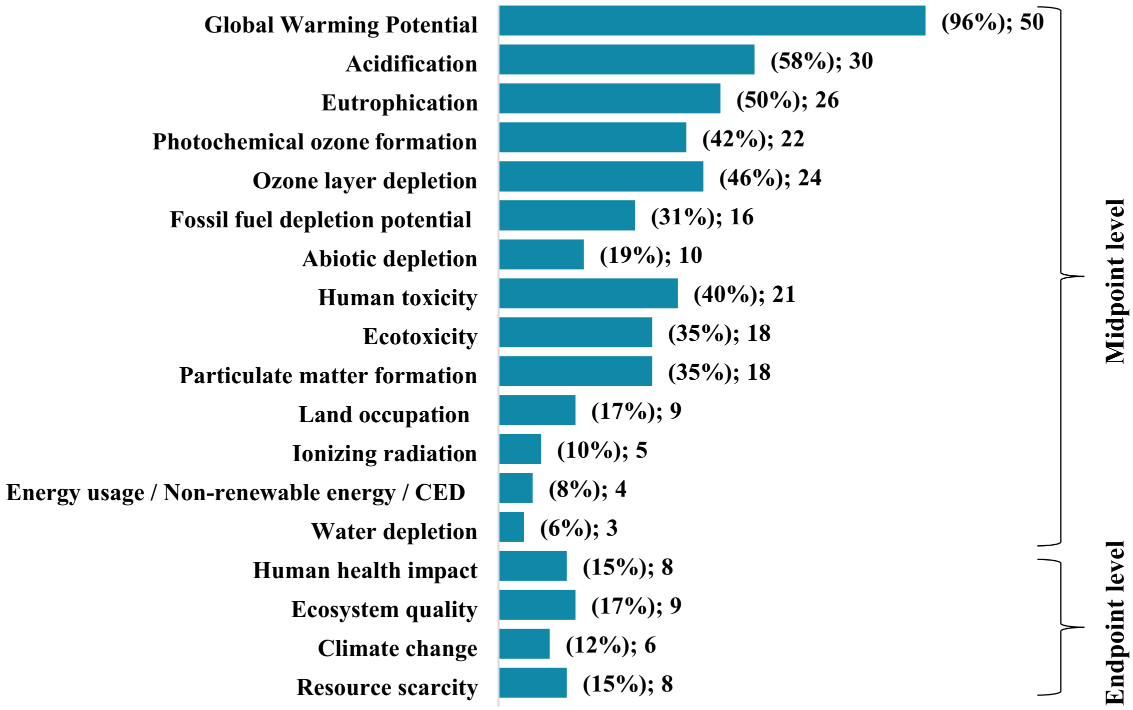


Fig. 9 Impact categories considered in the studies

in LCA studies of biomass densification. Muazu et al. (2017) reviewed several studies about biomass densification and detected the need for research to understand the significant variation in results and thus improve the robustness of LCA findings. The authors pointed out that LCA results should be reported with associated uncertainties to improve the clarity of results.

In the current review, some studies were identified as performing a sensitivity analysis of LCA results but did not include uncertainty analysis, such as De la Fuente et al. (2018), Li et al. (2012) and Wang et al. (2017), among others. Regarding uncertainties, Manandhar and Shah (2017) identified 14 input parameters with the potential for variation in process conditions related to fuel conversion efficiency, plant size, bale density, ash content, moisture content, and pelletizing energy. As for sensitivity analysis, pessimistic and optimistic values were considered in some studies. Adams et al. (2015) analyzed how the power of drying biomass influenced the result of LCA through low, medium, and high values of energy required.

Li et al. (2012) explored three scenarios: (i) pelletization energy consumption, (ii) type of fuel used in the drying process, and (iii) wheat straw moisture content before drying. Of these studies, 92.31% performed sensitivity analysis or included scenarios in assessment, and 17.31% provided information on uncertainties and the use of Monte Carlo Simulation. This indicates that the robustness of most LCA results in the literature for biomass densification is low, which may compromise the reliability of studies' results (Johnson et al. 2011).

Higher contribution process in environmental studies related to biomass densification

This section highlights the process(es) with the highest contribution to the environmental impact of biomass densification processes for each impact category considered in the studies. In this study, hotspots are processes that have the largest contribution to the total environmental impact in each impact category. The hotspots were ranked from most to least contribution impact processes. The processes and activities that contributed the most to the overall environmental effect were chosen using information from the figures, tables, and discussion as most of the studies do not provide a detailed breakdown of results in numerical terms, qualitative contributions were considered according to each of the relevant steps of the Cradle-to-gate and Cradle-to-grave approaches. The other approaches represent a low percentage of total studies, not appropriate for comparative purposes. Figures 10 and 11 summarize the main critical points identified in different studies analyzed.

The graphics show, for each one of the impact categories, the processes/activities that contributed the most, according to the authors of the reviewed articles. For example, in Fig. 10, in the Cradle-to-gate approach, human toxicity was evaluated by 7 authors (13.46% of the total of the reviewed studies), among which the densification process was the most contributing process in 4 studies, and 3 were assigned to biomass plantation, cultivation, and post-harvest.

The briquetting or pelleting process was identified as a hotspot in most of the impact categories (Fig. 10). This

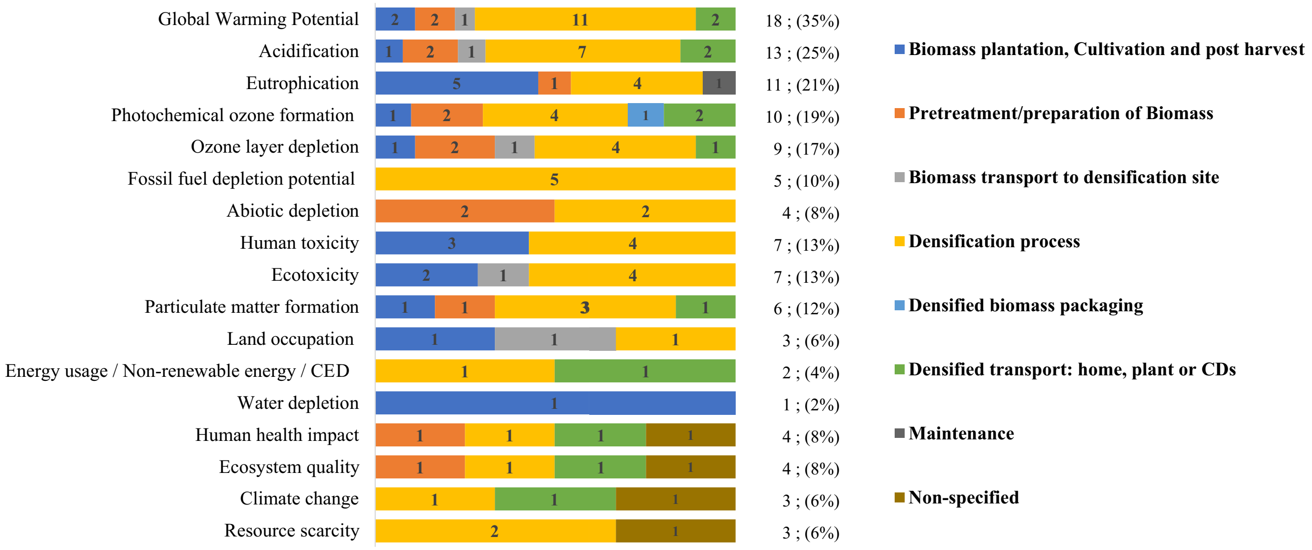


Fig. 10 Number of Cradle-to-gate studies that identify a certain process as a hotspot

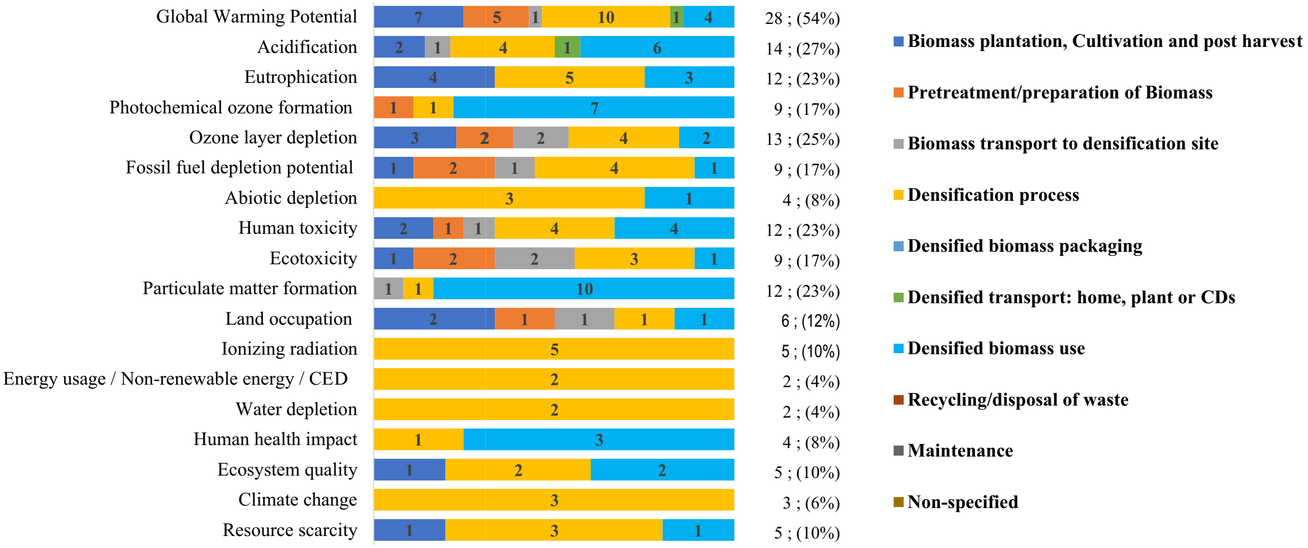


Fig. 11 Number of Cradle-to-grave studies that identify a certain process as a hotspot

is related to the fact that the briquetting or pelletizing process is dominated by the effect of significant use of machines, usually with high energy consumption, resulting in elevated emissions of CO_2 and CH_4 (Li et al. 2012), which contribute, for example, to the category of global warming.

Another important aspect was the impact of transport emissions, as described in the paper by Rousset et al. (2011). The authors considered domestic road transportation and maritime transportation from Brazil to the USA, both of which significantly impacted diesel consumption. It is essential to highlight the strong influence of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions on climate change. The authors highlighted that 10% of the CO_2 emissions were due to fossil fuel production and use in energy generation and transport processes. Every sector of the global economy produces greenhouse gases into the atmosphere, from industry to agriculture to transportation to power generation; thus, it is critical to understand the harmful impact of these gases. The quantification of emissions to different compartments such as air, water, and soil is critical for determining the effect of any material and its biodegradability, potential bioaccumulation, biodegradability, and interaction between compartments.

It is interesting to note that to achieve the required biomass moisture content, there may be considerable energy consumption and, consequently, a significant increase in impacts, as in the case of studies from Adams et al. (2015) and Li et al. (2012). They identified biomass drying as an activity with significant effects.

The production, harvesting, and preparation of biomass are stages that contribute to eutrophication since the biomass used in some studies incorporated fertilizers in production, as reported by Li et al. (2012). Additionally, electricity production, equipment used in densification, production, and fuel use are critical factors in this impact category.

As for the Cradle-to-grave approach, the impacts are like the Cradle-to-gate approach, with the briquetting or pelletizing processes being the most influential. As reported by Wang et al. (2017) and Benetto et al. (2015), the impact categories of photochemical ozone formation, particulate matter formation, and human health impact reflect how the use of these densified products can impact the environment (Fig. 11). This is frequently caused by a mixture of secondary pollutants formed by reactions between nitrogen oxides and volatile organic compounds (Gad 2014), which are released during the incomplete combustion and evaporation of these products or other fuels and solvents (Nogueira 2003). In practical terms, it is necessary to conduct comprehensive LCA studies, including each of the phases of the life cycle of the product under study.

The specification of the system boundary means that the inventory data that must be collected and the allocation of impacts may differ depending on how such limits are established. As a result, defining boundaries is an important stage in LCA. Furthermore, doing comparative LCAs requires accurately establishing boundaries based on the same criteria for all systems under consideration. For example, Cradle-to-gate is not meant to analyze a process's whole life cycle, but the life cycle inventory (LCI) is relatively straightforward and quick to gather. The Cradle-to-grave evaluation can evaluate all life cycle assessments; however, the data collecting method is more difficult.

The approach of varied system boundaries may cause uncertainties as well as skewed results, making it hard to determine the environmental profile of the product in a substudy and affecting decision making (Igos et al. 2019; Muazu et al. 2017). As a result, it is vital to increase the transparency and clarity of the system boundaries in LCA studies on the densification process in order to fully comprehend the environmental impacts, future comparison with other studies, and policy-making. Therefore, it is essential to consider: (i) the necessity for alignment between both the system boundaries and, the aims and scope of the studies, (ii) the choice of which processes to include or exclude from the LCA study and (iii) the need to document of the system boundaries through complete and clear flow diagram and LCI publication (Albertí et al. 2019).

Conclusion

In this review of the LCA of biomass briquettes and pellets, the main divergences were identified among the studies. It showed that biomass densification's LCA provides different information regarding functional unit choice, product system, allocation adopted, LCIA method, and uncertainties.

Most studies in the literature do not provide essential information, such as the inclusion of capital assets, waste, and effluents, which may affect the results of the LCA.

Review results indicate that the majority of studies used global coverage LCIA models; therefore, there is a necessity for performing regionalized LCA derived mainly from the influence of region-specific characteristics where the LCA is conducted.

The impacts evaluated are concentrated on global warming, acidification, eutrophication, photochemical oxidant formation potential, and ozone depletion. Some studies restricted to one or a few impact categories have been identified. Most studies use methods whose characterization factors are already available.

The critical point in most studies is the energy consumption in the compaction processes (briquetting and pelletization), being responsible for the impact in a representative percentage of the categories evaluated in the studies. Nevertheless, it is important to highlight that most studies do not provide essential information, such as the inclusion of capital assets, waste, and effluents, which may affect the results of the LCA.

The studies show little pay close attention to detail in uncertainty, indicating that a more transparent uncertainty analysis in the modelled LCA is required.

To improve the transparency and clarity of the reported results, given the methodological choices of the analyzed LCA studies, the following measures are suggested:

- It is recommended to select functional unit in terms of energy when the product is primarily for energy objectives, as it represents the desired function of the product.
- Studies should include impact categories that are sensitive to the product, process, and the local context in which they occur, which highlights the need for regionalization.
- Studies could assess the necessity of considering other impact categories to provide a lot more detailed insight about the environmental impacts.
- Studies should quantify, when possible, atmospheric emissions from the unitary processes involved in the densification system to obtain an inventory with more details of the impacts arising from the stages.
- The LCA results should reflect the quality of the data and the accuracy (or uncertainty) of the inventory data collected or modeled to support the analysis of the robustness of the results and ensure transparency.

Appendix A

See Table 3.

Table 3 Summary of studies on LCA of biomass densification

Reference	Objective	Raw material	Conversion technology	System boundary	Function	FU	Method
Adams et al. (2015)	The study's primary goal was to analyze the ecological impacts of incorporating the torrefaction process into the alternative energy supply chain	Pine logs and forest residues	Pelletizing	Cradle-to-gate	Electricity	1 t	Recipe
Alanya-Rosenbaum et al. (2018)	The purpose of this research was to contrast the environmental performance of near-woods briquetting of post-harvest logging slash or forest leftovers in the Pacific Northwest area of the USA in 2016 with two other biofuels	Logging (forest) residues	Briquetting	Cradle-to-grave	Heat	1 MJ	TRACI
Arteaga-Pérez et al. (2015)	The goal of this LCA was to examine different power generation processes that used lignocellulosic biomass as a fuel replacement in coal-fired energy plants	Coal with forest biomass	Pelletizing	Cradle-to-gate	Electricity	1 MJ	CML
Benetto et al. (2015)	The goal was to analyze and explain how the manufacture of grape marc pellets for heating in Luxembourg affected the environment overall Using attributional LCA	Grape marc	Pelletizing	Cradle-to-grave	Heat	1 MJ	Recipe
Bergman et al. (2014)	The goal was to conduct an inventory of the inputs and outputs related to switchgrass pellet manufacturing in the US Southeast year 2010	Switchgrass	Pelletizing	Cradle-to-gate	Heat	1 t	TRACI
Buchholz et al. (2017)	The study provided below sought to investigate the GHG consequences of locally sourced, manufactured, and consumed wood pellets for heating purposes, taking into account both the biogenic and fossil-fuel carbon cycles. To account for an uncertain future, the method comprised a thorough LCA framework that assessed a variety of potential forest market scenarios	Wood	Pelletizing	Cradle-to-grave	Heat	1 kWh	Other
Cespi et al. (2014)	The current work used life cycle assessment (LCA) techniques to develop a model for assessing the environmental implications of two wood-burning combustion systems: a wood stove and a pellet stove	Wood residues	Pelletizing	Cradle-to-grave	Heat	1 MJ	Recipe

Table 3 (continued)

Reference	Objective	Raw material	Conversion technology	System boundary	Function	FU	Method
Chaisuwan et al. (2020)	The goal of this research was to compare the LCA of carbonized briquettes made from rain tree leftovers and coffee grounds/tea debris to typical waste management methods for these residues	Rain tree residues and coffee grounds/tea waste	Briquetting	Cradle-to-grave	Heat	150 g/unit	CML
Chiew and Shimada (2013)	The goal was to provide a foundational data collection for assessing the environmental effect of these technologies using the life cycle assessment (LCA) methodology	Empty fruit bunches	Briquetting	Gate-to-gate	Electricity	1 t	CML
Clare et al. (2015)	As a result, the economic viability and carbon abatement potential of biochar synthesis by pyrolysis were compared to those of bioenergy production via briquetting and gasification in this research	Straw resources	Briquetting	Cradle-to-grave	Heat	1 t	IPCC
De la Fuente et al. (2018)	This study aimed to provide answers to these issues by evaluating the environmental characteristics of small-scale decentralized mobile manufacturing systems for pelletizing logging wastes in Northern Sweden under two operational contexts: landing-based and terminal-based	Logging residues	Pelletizing	Gate-to-gate	Non-specified	1 t	Recipe
Dias et al. (2017)	The goal of this research was to determine the environmental and energy implications of producing 1 MJ of thermal energy from direct combustion of short rotation willow (SRW) pellets	Short-rotation willow biomass	Pelletizing	Cradle-to-grave	Heat	1 MJ	TRACI
Dwivedi et al. (2011)	The purpose of this study was to assess the global warming effect (GWI) of import wood pellets from the southern USA used for power generation in The Netherlands	Wood	Pelletizing	Cradle-to-grave	Electricity	1 kWh	TRACI
Fantozzi and Buratti (2010)	The research' goal was to examine the impact on the environment of wood pellet consumption for thermal energy production across a life cycle	Short rotation coppice	Pelletizing	Cradle-to-grave	Heat	1 MJ	EcoIndicator 99 EPS 2000 EDIP

Table 3 (continued)

Reference	Objective	Raw material	Conversion technology	System boundary	Function	FU	Method
Ferreira et al. (2018)	The goal of this study was to address this issue by measuring and contrasting the environmental impact of 1 MJ of heat generated from grape stem and wood pellets using the life-cycle-assessment approach	Grape stalk	Pelletizing	Gate-to-grave	Heat	1 MJ	CML
Giuntoli et al. (2015)	The goal was to propose an LCA that connects these diverse components of bioenergy's environmental impact in a research study including residential heating generation from forest logging leftovers	Logging residues	Pelletizing	Cradle-to-grave	Heat	1 MJ	ILCD 2011
Hossain et al. (2016)	The primary goal of this research was to evaluate the appropriateness and sustainability of biofuel generation from recovered wood waste, as well as its prospective use in Hong Kong	Wood wastes	Pelletizing	Cradle-to-grave	Heat	1 kWh	Impact 2002 +
Hu et al. (2014)	This article presents a thorough assessment of these effects for a fully operational 2X104 t/a cornstalk briquette fuel factory in China	Corn stalk	Briquetting	Cradle-to-grave	Electricity	1 MWh	IPCC
Kylili et al. (2016)	The goal of this article was to execute an LCA to investigate the environmental impacts of the pelleting process utilizing waste olive husk for the manufacturing of pellets for home heating in Cyprus	Olive husk	Pelletizing	Cradle-to-gate	Heat	1 t	ILCD 2011
Laschi et al. (2016)	This study aimed to assess both the environmental implications of high-quality pellet production and the critical activities or processes throughout the production chain using a Cradle-to-gate approach and the LCA perspective. Special consideration was also given to forest operations in order to assess the contribution of wood extraction to global environmental loads	The residual woody	Pelletizing	Cradle-to-gate	Fuel	1 kg	Recipe
Li et al. (2012)	The purpose of this research was to characterize and calculate the resource consumption and environmental implications associated with the whole life cycle of wheat straw pellet manufacturing	Wheat straw	Pelletizing	Cradle-to-gate	Heat	1 kg	CML

Table 3 (continued)

Reference	Objective	Raw material	Conversion technology	System boundary	Function	FU	Method
Lu et al. (2015)	The purpose of this LCA research was to evaluate the possible environmental implications of wheat straw pellet manufacturing using various pretreatment procedures	Wheat straw	Pelletizing	Cradle-to-gate	Heat	1 kg	CML
Manandhar and Shah (2017)	The purpose of this research is to evaluate the environmental consequences of biomass densification in bale and pellet formats on three prospective maize stover feedstock transport scenarios for a lignocelluloses biorefinery in the Midwest of the USA	Corn stover	Pelletizing	Cradle-to-gate	Fuel-electricity	1 t	TRACI
Manouchehrinejad et al. (2020)	The goal is to calculate the energy consumption, emission, and minimum selling price (MSP) of electricity and thermal heat produced from Napier grass as contrasted to coal or natural gas-fired combined heating and power producing facility	Napier grass	Pelletizing	Cradle-to-grave	Heat-electricity	1 MJ	TRACI
Murphy et al. (2013)	The study sought to assess the implications of changes in essential factors on the system's total environmental impact	Miscanthus	Pelletizing and briquetting	Cradle-to-gate	Heat-electricity	1 GJ	CML
Murphy et al. (2015)	The goal of this research was to contribute to the current LCA insights of forest operations in Ireland by analyzing the next stage in the wood industry	Pulpwood	Pelletizing	Cradle-to-gate	Heat	1 t	IPCC
Nguyen et al. (2014)	The goal was to assess the geographical variability of life cycle environmental effects caused by features throughout the biomass feedstock supply chain that are subject to variation due to the amount of biomass harvested, collected, stored, transferred, and preprocessed prior to long-distance transit to a centralized biorefinery	Corn stover	Pelletizing	Gate-to-gate	Fuel	1 MJ	IPCC
Njenga et al. (2014)	The current study examined the potential advantages of recycling charcoal dust into charcoal briquettes regarding reduced GHG emissions and greater cooking fuel availability	Charcoal dust	Operating Manual	Cradle-to-grave	Heat	Cooking 1 kg of food	IPCC

Table 3 (continued)

Reference	Objective	Raw material	Conversion technology	System boundary	Function	FU	Method
Pa et al. (2012)	The goal is to calculate the environmental profile of each 1 ton of BC wood pellets sent to Europe in the midpoint approach	Sawmill residues	Pelletizing	Cradle-to-gate	Heat	1 t	Impact 2002+
Pergola et al. (2018)	The purpose of this study was to quantify and analyze the environmental effects and costs of producing packed wood pellets	Roundwood logs and sawdust	Pelletizing	Cradle-to-gate	Heat	1 t	Impact 2002+
Perić et al. (2018)	The goal of this study was to evaluate Miscanthus' environmental impact in order to begin using it as a viable source of energy in domestic heating systems in the Republic of Serbia	Miscanthus	Briquetting	Cradle-to-grave	Heat	1 ha	Recipe
Porsö and Hansson (2014)	The general goal of this study was to investigate the environmental impacts of expanding pellet manufacturing from new indigenous raw resources in Sweden	Willow and poplar	Pelletizing	Cradle-to-grave	Heat	1 GJ	IPCC
Porsö et al. (2018)	The purpose of this study was to assess and contrast the energy efficiency and climatic effect of producing and using non-torrefied and torrefied wood pellets	Logging residues	Pelletizing	Cradle-to-grave	Electricity	1 GJ	IPCC
Quinteiro et al. (2019)	The goal of this research was to evaluate the environmental implications of five different wood-based domestic heating in Portugal	Wood and wood split logs	Pelletizing	Cradle-to-grave	Heat	1 MJ	Recipe
Quinteiro et al. (2020)	The goal of this study was to assess the environmental profiles of one centralised and two decentralized wood pellet manufacture systems for domestic heating in Portugal	Maritime pine wood	Pelletizing	Cradle-to-grave	Heat	1 MJ	Recipe
Rajabi Hamedani et al. (2019)	The goal of this LCA research was to evaluate and assess the environmental implications of producing pellets from orchard woody biomass	Vine and olive grove woody biomass	Pelletizing	Cradle-to-gate	Heat	1 MJ	Recipe
Reed et al. (2012)	The purpose of the research was to evaluate the Cradle-to-gate LCI of producing packaged wood pellets using hardwood materials in the Southeast US pellet-manufacturing region	Hardwood flooring residues	Pelletizing	Cradle-to-gate	Heat	1 t	TRACI

Table 3 (continued)

Reference	Objective	Raw material	Conversion technology	System boundary	Function	FU	Method
Röder et al. (2015)	The goal was to investigate the burning of wood pellets derived from forest leftovers to create power, as well as the uncertainties associated with GHG emissions that arise at various points throughout the supply chain	Forest and sawmill residues	Pelletizing	Cradle-to-gate	Electricity	1 kWh	CML
Rousset et al. (2011)	The goal of this research was to define the environmental effect evaluation, specifically those linked with the Global Warming Potential (GWP) of wood charcoal briquettes manufactured from eucalyptus wood in Brazil for use as an energy supply in meal preparation	Charcoal fines	Briquetting	Cradle-to-gate	Heat	1 kg	CML
Ruhul Kabir and Kumar (2012)	This study aimed to assess the life cycle energy and environmental performance of 9 different biomass/coal co-firing power production processes	Agricultural residue	Pelletizing	Cradle-to-grave	Electricity	1 MWh	Other
Saba et al. (2020)	It examined the significant environmental impacts of all phases of a biomass briquette's life cycle, from raw material extraction to processing, production, distribution, usage, and disposal	Olive pruning residues	Briquetting	Cradle-to-grave	Heat	1 MJ	Impact 2002 +
Saosee et al. (2020)	The goal of this study is to analyze the environmental implications of eight different types of wood pellet production, which differ in terms of raw materials, manufacturing methods, energy consumption, and transportation distance	Different types of wood	Pelletizing	Cradle-to-gate	Heat	1 t	Recipe
Sgarbossa et al. (2020)	The purpose of this research is to assess and compare the environmental effect of various wood pellet supply chains	Sawdust	Pelletizing	Cradle-to-grave	Heat	1 MJ	CML
Shen et al. (2015)	The goal of this article is to focus on power generation from ignocellulosic material and compare the effects of different biomass resources, transportation, and power generating systems as evaluated by life cycle assessment (LCA)	Lignocellulosic biomass	Pelletizing	Cradle-to-grave	Electricity	1 t	Other
Sjølie and Solberg (2011)	This study aimed to examine the resource consumption and GHG emissions associated with the manufacturing, transportation, use, and ash treatment of wood pellets manufactured at Averya in western Norway. The authors did a sensitivity analysis to vary some key factors	The birch tree	Pelletizing	Cradle-to-grave	Electricity	1 t	IPCC

Table 3 (continued)

Reference	Objective	Raw material	Conversion technology	System boundary	Function	FU	Method
Sultana and Kumar (2011)	The purpose of this work was to examine pellet manufacture from agricultural residue, particularly wheat straw, in the context of energy consumption and emission during its life cycle	Wheat straw	Pelletizing	Cradle-to-grave	Heat	1 MJ	IPCC
Tabata and Okuda (2012)	The goal of this research was to establish a woody biomass-based energy system to replace the present fossil-fuel-based system, lowering both prices and impact on the environment	Woody biomass	Pelletizing	Cradle-to-grave	Heat	1 t	Other
Tsalidis et al. (2014)	The purpose of this article was to assess the environmental benefits of biomass direct co-firing with coal on a 20 percent energy input basis, as compared to coal-fired power production in The Netherlands	Waste woody biomass	Pelletizing	Cradle-to-gate	Electricity	1 kWh	CML
Valente et al. (2011)	The purpose of this research is to offer an example of an alpine forest fuel system that performs a LCA by combining the harvesting of logging wastes with the harvesting of traditional wood products (saw logs)	Logging residues and saw logs	Pelletizing	Cradle-to-grave	Heat	1 m^3	IPCC
Vera et al. (2020)	The research's primary purpose was to evaluate supply-chain possibilities for multioutput biorefineries using globally supplied cellulase to find the best supply-chain architecture in terms of GHG emissions	Stem wood and Bagasse	Pelletizing	Cradle-to-gate	Fuel	1 MJ	Carbon footprints
Villabona and Kafarov (2018)	This study aimed to investigate the environmental impact of agricultural biomass combustion processes using the life-cycle-assessment approach	Rice husk	Pelletizing	Cradle-to-cradle	Electricity	1 kg	Recipe
Wang et al. (2017)	The aim was to examine of the environmental implications of the life cycle stages of cornstalk growth, cornstalk transportation, briquette fuel manufacturing, transportation, and utilization	Cornstalk	Briquetting	Cradle-to-grave	Fuel	1 t	Recipe

Acknowledgements The CNPq—Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for financial support for this research and the Federal Technological University of Paraná—UTFPR for providing the necessary resources for the development of this research. Grant number: 440179/2019-0.CMLU receives a productivity fellowship from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

Adams PWR, Shirley JEJ, McManus MC (2015) Comparative Cradle-to-gate life cycle assessment of wood pellet production with torrefaction. Appl Energy 138:367–380. https://doi.org/10.1016/j.apenergy.2014.11.002

Alanya-Rosenbaum S, Bergman RD, Ganguly I, Pierobon F (2018) A comparative life-cycle assessment of briquetting logging residues and lumber manufacturing coproducts in western United States. Appl Eng Agric 34(1):11–24. https://doi.org/10.13031/aea.12378

Albertí J, Roca M, Brodhag C, Fullana-i-Palmer P (2019) Allocation and system boundary in life cycle assessments of cities. Habitat Int 83:41–54. https://doi.org/10.1016/j.habitatint.2018.11.003

Arteaga-Pérez LE, Vega M, Rodríguez LC, Flores M, Zaror CA, Ledón YC (2015) Life-cycle assessment of coal–biomass based electricity in Chile: focus on using raw vs torrefied wood. Energy Sustain Dev 29:81–90. https://doi.org/10.1016/j.esd.2015.10.004

Azapagic A, Clift R (1999) Allocation of environmental burdens in multiple-function systems. J Clean Prod 7:101–119. https://doi.org/10.1016/S0959-6526(98)00046-8

Bajwa DS, Peterson T, Sharma N, Shojaeiarani J, Bajwa SG (2018) A review of densified solid biomass for energy production. Renew Sustain Energy Rev 96:296–305. https://doi.org/10.1016/j.rser.2018.07.040

Benetto E, Jury C, Kneip G, Vázquez-Rowe I, Huck V, Minette F (2015) Life cycle assessment of heat production from grape marc pellets. J Clean Prod 87:149–158. https://doi.org/10.1016/j.jclepro.2014.10.028

Bergman R, Reed DL, Taylor AM, Harper DP, Hodges DG (2014) Cradle-to-gate life cycle assessment of switchgrass fuel pellets manufactured in the Southeastern United States. Wood Fiber Sci 47:147–159

Bioenergy International (2019) Minister Bruton announces Support Scheme for Renewable Heat. Bioenergy International. https://bioenergyinternational.com/policy/minister-bruton-announces-support-for-renewable-heat. Accessed 26 August 2020

Brugnera AB (2016) Estudo da produção de briquetes com resíduos da indústria de carvão com aglutinantes. Universidade Estadual do Centro-Oeste, Guarapuava

Buchholz T, Gunn JS, Saah DS (2017) Greenhouse gas emissions of local wood pellet heat from northeastern US forests. Energy 141:483–491. https://doi.org/10.1016/j.energy.2017.09.062

Burck J, Hagen U, Höhne N, Nascimento L, Bals C (2019) Climate change performance index: results 2020 (Anual), CCPI. Instituto NewClimate, ONG Germanwatch e Climate Action Network, Alemannia

Cabuzel T (2019) EU climate action and the European Green Deal [WWW Document]. Climate Action - European Commission. https://ec.europa.eu/clima/policies/eu-climate-action_en. Accessed 8 June 2020

Cespi D, Passarini F, Ciacci L, Vassura I, Castellani V, Collina E, Piazzalunga A, Morselli L (2014) Heating systems LCA: comparison of biomass-based appliances. Int J Life Cycle Assess 19:89–99. https://doi.org/10.1007/s11367-013-0611-3

Chaisuwan N, Kansai N, Supakata N, Papong S (2020) The comparison of environmental impacts of carbonized briquettes from rain tree residues and coffee grounds/tea waste and traditional waste management. Int J Environ Sci Dev 11:48–53. https://doi.org/10.18178/ijesd.2020.11.1.1224

Chiew YL, Shimada S (2013) Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer: a case study of Malaysia. Biomass Bioenerg 51:109–124. https://doi.org/10.1016/j.biombioe.2013.01.012

Clare A, Shackley S, Joseph S, Hammond J, Pan G, Bloom A (2015) Competing uses for China's straw: the economic and carbon abatement potential of biochar. GCB Bioenergy 7:1272–1282. https://doi.org/10.1111/gcbb.12220

Cleary J (2009) Life cycle assessments of municipal solid waste management systems: a comparative analysis of selected peer-reviewed literature. Environ Int 35:1256–1266. https://doi.org/10.1016/j.envint.2009.07.009

Cloete S (2019) An independent Global Energy Forecast to 2050 (part 4 of 5): nuclear, biomass and CCS. Energy Post. https://energypost.eu/an-independent-global-energy-forecast-to-2050-part-4-of-5-nuclear-biomass-and-ccs/. Accessed 27 August 2020

De Fontes PJ, Okino EYA, Quirino WF (1989) Aspectos Técnicos da Briquetagem do Carvão Vegetal no Brasil, Série Técnica N^{o} 1. Laboratório de Produtos Florestais -LPF, Brasília

De la Fuente T, Bergström D, González-García S, Larsson SH (2018) Life cycle assessment of decentralized mobile production systems for pelletizing logging residues under Nordic conditions. J Clean Prod 201:830–841. https://doi.org/10.1016/j.jclepro.2018.08.030

Dias GM, Ayer NW, Kariyapperuma K, Thevathasan N, Gordon A, Sidders D, Johannesson GH (2017) Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada. Appl Energy 204:343–352. https://doi.org/10.1016/j.apenergy.2017.07.051

de Dias JMCS, de Souza DT, Braga M, Onoyama MM, Miranda CHB, Barbosa PFD, Rocha JD (2012) Produção de briquetes e péletes a partir de resíduos agrícolas, agroindustriais e florestais, 1a edição. ed, 13. Embrapa Agroenergia, Brasília, DF

Donato D, Silva C, Magalhães M, Araújo Júnior C, Carneiro A, Vital B (2015) Propriedades de Briquetes Obtidos de Finos de Carvão Vegetal. Revista Ciência da Madeira - RCM 6, pp 107–111. https://doi.org/10.12953/2177-6830/rcm.v6n2p107-111

Dwivedi P, Bailis R, Bush TG, Marinescu M (2011) Quantifying GWI of wood pellet production in the Southern United States and its subsequent utilization for electricity production in the Netherlands/Florida. Bioenerg Res 4:180–192. https://doi.org/10.1007/s12155-010-9111-5

Ekvall T, Finnveden G (2001) Allocation in ISO 14041—a critical review. J Clean Prod 9:197–208. https://doi.org/10.1016/S0959-6526(00)00052-4

Fantozzi F, Buratti C (2010) Life cycle assessment of biomass chains: Wood pellet from short rotation coppice using data measured on a real plant. Biomass Bioenergy 34:1796–1804. https://doi.org/10.1016/j.biombioe.2010.07.011

Ferreira J, Esteves B, Cruz-Lopes L, Evtuguin DV, Domingos I (2018) Environmental advantages through producing energy from grape stalk pellets instead of wood pellets and other sources. Int J Environ Stud 75:812–826. https://doi.org/10.1080/00207233.2018.1446646

Frankfurt School – UNEP (2019) Global trends in renewable energy investment 2019. Frankfurt School-UNEP Centre/BNEF, Alemannia

Frischknecht R, Jolliet O (2019) Global guidance for life cycle impact assessment indicators, vol 2. UNEP/SETAC Life Cycle Initiative, Paris

Gad SC (2014) Photochemical oxidants. In: Wexler P (eds) Encyclopedia of toxicology, 3rd edn. Academic Press, Oxford, pp 926–927. https://doi.org/10.1016/B978-0-12-386454-3.00906-4

Gef TGEF, UNDP (2019) 2019 Project implementation report (No. 4718). The Global Environment Facility, Brazil

Giuntoli J, Caserini S, Marelli L, Baxter D, Agostini A (2015) Domestic heating from forest logging residues: environmental risks and benefits. J Clean Prod 99:206–216. https://doi.org/10.1016/j.jclepro.2015.03.025

Harvey H, Orvis R, Rissman J (2019) Designing climate solutions: a policy guide for low-carbon energy, 1st edn. Island Press, Washington

Hossain MdU, Leu S-Y, Poon CS (2016) Sustainability analysis of pelletized bio-fuel derived from recycled wood product wastes in Hong Kong. J Clean Prod 113:400–410. https://doi.org/10.1016/j.jclepro.2015.11.069

Hu J, Lei T, Wang Z, Yan X, Shi X, Li Z, He X, Zhang Q (2014) Economic, environmental and social assessment of briquette fuel from agricultural residues in China: a study on flat die briquetting using corn stalk. Energy 64:557–566. https://doi.org/10.1016/j.energy.2013.10.028

Igos E, Benetto E, Meyer R, Baustert P, Othoniel B (2019) How to treat uncertainties in life cycle assessment studies? Int J Life Cycle Assess 24:794–807. https://doi.org/10.1007/s11367-018-1477-1

ISO IO for S (2006a) Environmental management—life cycle assessment—principles and framework

ISO IO for S (2006b). ISO 14044: 2006b environmental management—life cycle assessment—requirements and guidelines

Johnson DR, Willis HH, Curtright AE, Samaras C, Skone T (2011) Incorporating uncertainty analysis into life cycle estimates of greenhouse gas emissions from biomass production. Biomass Bioenergy 35:2619–2626. https://doi.org/10.1016/j.biombioe.2011.02.046

JRC (2011) International reference life cycle data system (ILCD) handbook-recommendations for life cycle impact assessment in the European context. EU Science Hub-European Commission

Kylili A, Christoforou E, Fokaides PA (2016) Environmental evaluation of biomass pelleting using life cycle assessment. Biomass Bioenergy 84:107–117. https://doi.org/10.1016/j.biombioe.2015.11.018

Laschi A, Marchi E, González-García S (2016) Environmental performance of wood pellets' production through life cycle analysis. Energy 103:469–480. https://doi.org/10.1016/j.energy.2016.02.165

Lenzen M (2006) Uncertainty in impact and externality assessments-implications for decision-making (13 pp). Int J Life Cycle Assess 11:189–199. https://doi.org/10.1065/lca2005.04.201

Li X, Mupondwa E, Panigrahi S, Tabil L, Adapa P (2012) Life cycle assessment of densified wheat straw pellets in the Canadian Prairies. Int J Life Cycle Assess 17:420–431. https://doi.org/10.1007/s11367-011-0374-7

Liu W, Yu Z, Xie X, von Gadow K, Peng C (2018) A critical analysis of the carbon neutrality assumption in life cycle assessment of forest bioenergy systems. Environ Rev 26:93–101. https://doi.org/10.1139/er-2017-0060

Lu D, Tabil LG, Wang D, Li X, Mupondwa E (2015) Comparison of pretreatment methods for wheat straw densification by life cycle assessment study. Trans ASABE 58:453–464. https://doi.org/10.13031/trans.58.10510

Manandhar A, Shah A (2017) Life cycle assessment of feedstock supply systems for cellulosic biorefineries using corn stover transported in conventional bale and densified pellet formats. J Clean Prod 166:601–614. https://doi.org/10.1016/j.jclepro.2017.08.083

Manouchehrinejad M, Sahoo K, Kaliyan N, Singh H, Mani S (2020) Economic and environmental impact assessments of a stand-alone napier grass-fired combined heat and power generation system in the southeastern US. Int J Life Cycle Assess 25:89–104. https://doi.org/10.1007/s11367-019-01667-x

Mayer F, Bhandari R, Gäth S (2019) Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. Sci Total Environ 672:708–721. https://doi.org/10.1016/j.scitotenv.2019.03.449

Miranda-Santos SDFDO, Piekarski CM, Ugaya CML, Donato DB, Braghini-Júnior A, De Francisco AC, Carvalho AMML (2017) Life Cycle Analysis of Charcoal Production in Masonry Kilns with and without Carbonization Process Generated Gas Combustion. Sustainability 9:1558. https://doi.org/10.3390/su9091558

MoEn (2019) Ghana renewable energy master plan. Ministry of Energy, Ghana

Muazu RI, Borrion AL, Stegemann JA (2017) Life cycle assessment of biomass densification systems. Biomass Bioenergy 107:384–397. https://doi.org/10.1016/j.biombioe.2017.10.026

Muench S, Guenther E (2013) A systematic review of bioenergy life cycle assessments. Appl Energy 112:257–273. https://doi.org/10.1016/j.apenergy.2013.06.001

Murphy F, Devlin G, McDonnell K (2015) Greenhouse gas and energy based life cycle analysis of products from the Irish wood processing industry. J Clean Prod 92:134–141. https://doi.org/10.1016/j.jclepro.2015.01.001

Murphy F, Devlin G, McDonnell K (2013) Miscanthus production and processing in Ireland: an analysis of energy requirements and environmental impacts. Renew Sustain Energy Rev 23:412–420. https://doi.org/10.1016/j.rser.2013.01.058

Nguyen L, Cafferty KG, Searcy EM, Spatari S (2014) Uncertainties in life cycle greenhouse gas emissions from advanced biomass feedstock logistics supply chains in Kansas. Energies 7:7125–7146. https://doi.org/10.3390/en7117125

Njenga M, Karanja N, Karlsson H, Jamnadass R, Iiyama M, Kithinji J, Sundberg C (2014) Additional cooking fuel supply and reduced global warming potential from recycling charcoal dust into charcoal briquettes in Kenya. J Clean Prod 81:81–88. https://doi.org/10.1016/j.jclepro.2014.06.002

Nogueira LAH (2003) Dendroenergia - Fundações e Aplicações, 2a edn. Interciência, Rio de Janeiro

Pa A, Craven JS, Bi XT, Melin S, Sokhansanj S (2012) Environmental footprints of British Columbia wood pellets from a simplified life cycle analysis. Int J Life Cycle Assess 17:220–231. https://doi.org/10.1007/s11367-011-0358-7

Pergola M, Gialdini A, Celano G, Basile M, Caniani D, Cozzi M, Gentilesca T, Mancini IM, Pastore V, Romano S, Ventura G, Ripullone F (2018) An environmental and economic analysis of the wood-pellet chain: two case studies in Southern Italy. Int J Life Cycle Assess 23:1675–1684. https://doi.org/10.1007/s11367-017-1374-z

Perić M, Komatina M, Antonijević D, Bugarski B, Dželetović Ž (2018) Life cycle impact assessment of miscanthus crop for sustainable household heating in Serbia. Forests 9:654. https://doi.org/10.3390/f9100654

Porsö C, Hammar T, Nilsson D, Hansson P-A (2018) Time-dependent climate impact and energy efficiency of internationally traded non-torrefied and torrefied wood pellets from logging residues. Bioenergy Res 11:139–151

Porsö C, Hansson P-A (2014) Time-dependent climate impact of heat production from Swedish willow and poplar pellets—in a life cycle perspective. Biomass Bioenergy 70:287–301. https://doi.org/10.1016/j.biombioe.2014.09.004

Potting J, Hertel O, Schöpp W, Bastrup-Birk A (2006) Spatial differentiation in the characterisation of photochemical ozone formation: the EDIP2003 methodology. Int J Life Cycle Assess 11:72–80. https://doi.org/10.1065/lca2006.04.014

Quinteiro P, Greco F, da Cruz Tarelho LA, Righi S, Arroja L, Dias AC (2020) A comparative life cycle assessment of centralised and decentralised wood pellets production for residential heating. Sci Total Environ 730:139162. https://doi.org/10.1016/j.scitotenv.2020.139162

Quinteiro P, Tarelho L, Marques P, Martín-Gamboa M, Freire F, Arroja L, Dias AC (2019) Life cycle assessment of wood pellets and wood split logs for residential heating. Sci Total Environ 689:580–589. https://doi.org/10.1016/j.scitotenv.2019.06.420

Quirino WF, Brito JO (1991) Características e índice de combustão de briquetes de carvão vegetal. IBAMA, Laboratório de Produtos Florestais Brasilia, Brazil

Raicv (2019). Recomendação de modelos de Avaliação de Impacto do Ciclo de Vida para o contexto brasileiro. Ibict, Brasília, DF

Rajabi Hamedani S, Colantoni A, Gallucci F, Salerno M, Silvestri C, Villarini M (2019) Comparative energy and environmental analysis of agro-pellet production from orchard woody biomass. Biomass Bioenergy 129:105334. https://doi.org/10.1016/j.biombioe.2019.105334

Reed D, Bergman R, Kim J-W, Taylor A, Harper D, Jones D, Knowles C, Puettmann ME (2012) Cradle-to-gate life-cycle inventory and impact assessment of wood fuel pellet manufacturing from hardwood flooring residues in the Southeastern United States*. Forest Products J 62:280–288. https://doi.org/10.13073/FPJ-D-12-00015.1

REN21 (2019) Renewables 2019 global status report. In: Global status report. REN21 Secretariat, Paris

Rendeiro G, Nogueira MFM, Brasil ACDM, Cruz DODA, Guerra DRDS, Macêdo EN, de Araújo Ichihara J (2008) Combustão e gasificação de biomassa sólida, 1a ed. Ministério de Minas e Energia (MME), Brasília

Röder M, Whittaker C, Thornley P (2015) How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. Biomass Bioenergy 79:50–63. https://doi.org/10.1016/j.biombioe.2015.03.030

Rodriguez GS, Helmer LJ, Devens MCM, Fonseca PR, Simonelli G (2017) Produção de briquetes para queima utilizando finos da produção de carvão vegetal e glicerina. Holos 01

Rousset P, Caldeira-Pires A, Sablowski A, Rodrigues T (2011) LCA of eucalyptus wood charcoal briquettes. J Clean Prod 19:1647–1653. https://doi.org/10.1016/j.jclepro.2011.05.015

Ruhul Kabir M, Kumar A (2012) Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. Biores Technol 124:394–405. https://doi.org/10.1016/j.biortech.2012.07.106

Saba S, El Bachawati M, Malek M (2020) Cradle to grave life cycle assessment of Lebanese biomass briquettes. J Clean Prod 253:119851. https://doi.org/10.1016/j.jclepro.2019.119851

Sandin G, Røyne F, Berlin J, Peters GM, Svanström M (2015) Allocation in LCAs of biorefinery products: implications for results and decision-making. J Clean Prod 93:213–221. https://doi.org/10.1016/j.jclepro.2015.01.013

Saosee P, Sajjakulnukit B, Gheewala SH (2020) Life cycle assessment of wood pellet production in Thailand. Sustainability 12:6996. https://doi.org/10.3390/su12176996

Sgarbossa A, Boschiero M, Pierobon F, Cavalli R, Zanetti M (2020) Comparative life cycle assessment of bioenergy production from different wood pellet supply chains. Forests 11:1127. https://doi.org/10.3390/f11111127

Shen X, Kommalapati RR, Huque Z (2015) The comparative life cycle assessment of power generation from lignocellulosic biomass. Sustainability 7:12974–12987. https://doi.org/10.3390/su71012974

Silva FB, Yoshida OS, Diestelkamp ED, de Oliveira LA (2018) Relevance of including capital goods in the life cycle assessment of construction products. LALCA: Revista Latino-Americana em Avaliação do Ciclo de Vida 2:7–22. https://doi.org/10.18225/lalca.v2iEspec.4350

Sjølie HK, Solberg B (2011) Greenhouse gas emission impacts of use of Norwegian wood pellets: a sensitivity analysis. Environ Sci Policy 14:1028–1040. https://doi.org/10.1016/j.envsci.2011.07.011

Speranza J, Romeirouciana V, Betiol L, Biderman R (2017) Monitoramento da implementação da política climática brasileira: implicações para a Contribuição Nacionalmente Determinada (Working Paper). World Resources Institute - Brasil, São Paulo, Brasil

Stelte W, Sanadi A, Shang L, Holm J, Ahrenfeldt J, Henriksen U (2012) Recent developments in biomass palletization: a review. Bioresources 7:4451–4490. https://doi.org/10.15376/biores.7.3.4451-4490

Sultana A, Kumar A (2011) Development of energy and emission parameters for densified form of lignocellulosic biomass. Energy 36:2716–2732. https://doi.org/10.1016/j.energy.2011.02.012

Tabata T, Okuda T (2012) Life cycle assessment of woody biomass energy utilization: Case study in Gifu Prefecture, Japan. Energy. In: The 24th international conference on efficiency, cost, optimization, simulation and environmental impact of energy, ECOS 2011 45, pp 944–951. https://doi.org/10.1016/j.energy.2012.06.064

Tsalidis G-A, Joshi Y, Korevaar G, de Jong W (2014) Life cycle assessment of direct co-firing of torrefied and/or pelletised woody biomass with coal in The Netherlands. J Clean Prod 81:168–177. https://doi.org/10.1016/j.jclepro.2014.06.049

Ugaya CML, de Loreto AC, Sturm G, Savioli JPPDD, Crippa J, Esquiaqui L, Juchen RT, de Araújo JB (2020) Faço o que eu digo: ACV ambiental, social e econômica do Gyro. Presented at the VII

Congresso Brasileiro sobre Gestão do Ciclo de Vida-GCV2020, Gramado (RS), p 7

Valente C, Spinelli R, Hillring BG (2011) LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). J Clean Prod 19:1931–1938. https://doi.org/10.1016/j.jclepro.2011.06.026

Vera I, Hoefnagels R, van der Kooij A, Moretti C, Junginger M (2020) A carbon footprint assessment of multi-output biorefineries with international biomass supply: a case study for the Netherlands. Biofuels Bioprod Biorefin 14:198–224. https://doi.org/10.1002/bbb.2052

Villabona YP, Kafarov V (2018) Methodology for the life cycle assessment (LCA) in combustion processes where the fuel is pelleted agricultural biomass. Chem Eng Trans 64:427–432. https://doi.org/10.3303/CET1864072

Wang Z, Lei T, Yang M, Li Z, Qi T, Xin X, He X, Ajayebi A, Yan X (2017) Life cycle environmental impacts of cornstalk briquette fuel in China. Appl Energy 192:83–94. https://doi.org/10.1016/j.apenergy.2017.01.071

Zheng L, Chen J, Zhao M, Cheng S, Wang L-P, Mang H-P, Li Z (2020) What could china give to and take from other countries in terms of the development of the biogas industry? Sustainability 12:1490. https://doi.org/10.3390/su12041490

Zumsteg JM, Cooper JS, Noon MS (2012) Systematic review checklist. J Ind Ecol 16:S12–S21. https://doi.org/10.1111/j.1530-9290.2012.00476.x