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Research paper

Life-cycle assessment of biochar production systems in tropical rural areas: Comparing flame curtain kilns to other production methods

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ABSTRACT

A life-cycle assessment (LCA) using end point methods was performed for the generation and sequestration of one kg biochar by various pyrolysis methods suitable for rural tropical conditions. Flame curtain kilns, a novel, simple and cost-effective technology of biochar generation, were compared to earth mound non-improved kilns, retort kilns with off-gases combustion, pyrolytic cook-stoves allowing the use of the gas flame for cooking purposes, and iv) gasifiers with electricity production. The impact categories of climate change, particulate matter emissions, land use effects, minerals and fossil fuels were combined to provide the overall impact of biochar generation.

In the LCA ranking, earth mound kilns were shown to have negative potential environmental impacts because of their gas and aerosol emissions. Flame curtain kilns had slightly lower potential impact than retort kilns and much lower impact than earth-mound kilns because of the avoidance of start-up wood and low material use and gas emissions. Making biochar from flame curtain kilns was observed to be environmentally neutral in a life-cycle perspective, as the production emissions were compensated for by carbon sequestration. Pyrolytic cook-stoves and gasifiers showed the most positive potential environmental impact in the LCA due to avoided firewood consumption and emissions from electricity generation, respectively.

The generation and sequestration of biochar *per se* by flame curtain kilns was not found to result in direct environmental benefits. Co-benefits in the form of rural applicability, cost-efficiency and agricultural effects due to soil improvement are needed to warrant biochar implementation by this method.

1. Introduction

Biochar is produced by the thermal treatment (>350 °C) of biomass under low-oxygen conditions and provides a method to sequester carbon. Biochar can be used for the immobilization of contaminants in water, soils or sediments [1–4], as well as for the improvement of crop productivity in weathered and eroded soils [5,6]. The production of biochar in modern industrial devices can be a highly controlled process with low gas emissions [7]. However, achieving the same results under rural tropical conditions, i.e., with poorly maintained technologies in very low income settings, is more challenging [8]. Emitted gases during the process include methane (CH_4), carbon monoxide (CO) and aerosols (smoke; $PM_{2.5}$ and PM_{10}), nitrogen oxides (NO and NO_2, together NO_x), as well as non-methane volatile organic matter (NMVOC), in addition to hydrogen. CO, aerosols and NO_x are deleterious to human health [9–11], and methane and aerosols can exacerbate anthropogenic radiative forcing [12,13]. Several biochar production methods for low-income rural conditions exist. Traditionally, *earth mound or earth covered pit kilns* have been used most frequently. They are free of investment cost, merely requiring some poles and sand to cover the pyrolyzing biomass. However, they are slow (several days [14]), and generate significant gas/aerosol emissions [15,16]. *Retort kilns* (Fig. S1) involve a higher material investment and partially combust

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pyrolysis gases, reduce gas emissions by about 75% and have relatively high conversion efficiencies of 30–45% [17]. *Biochar-producing pyrolytic cook-stoves* such as TLUDs (Top-Lit Up-Draft stoves) and Anila stoves [18] can generate biochar while providing heat for cooking. Advantages include that they burn cleanly thus reducing indoor air emissions, can use various biomass residues as feedstock and are fuel-efficient. Pyrolytic gases are mostly combusted in the flame front, reducing emissions of CO, CH_4 and aerosols by around 75% [19,20] compared to open-fire or three-stone cooking. Even though the epidemiological evidence behind the relationship between indoor air emissions and premature death rates is scant [21], this can be considered an advantage. *Modern gasifier pyrolysis units* come at a much higher investment cost but lead to the lowest emission factors and allow for the generation of electricity avoiding electricity generation by off-grid fossil-fuel generators [7].

A recent development has been the introduction of the *Kon-Tiki* flame curtain kiln [8,22], which is fast compared to traditional kilns (hours instead of days), cost-effective and easy to operate. Flame curtain kilns come in two basic concepts: as a conical, all-steel deep-cone bowl (Fig. S1) and as a simple soil pit, consisting of a conically shaped hole in the ground which can be dug in a few hours and is essentially free of investment cost (Fig. S1). In a previous paper, we found the gas and particle emissions of various flame curtain kiln designs, including the soil pit design, to be universally low, lower still than those of retort kilns, especially for CO [22].

Life-cycle assessment (LCA) can compare the overall environmental impact of various alternatives for biochar generation and use. In several LCAs biochar production has been studied and various production methods have been compared. Ibarrola, Shackley [23] observed that slow pyrolysis systems offer better performance in terms of LCA climate impacts than fast pyrolysis and gasification, whereas gasification achieved the best electricity generation outputs. Peters, Iribarren [7] found that the best use of biochar in an overall LCA perspective is to use it as a replacement of fossil coal in power plants, provided the biochar is made in a modern, ultralow emission pyrolysis unit. In contrast, the overall environmental life cycle impact of biochar made in retort kilns under rural low-income conditions (Indonesia) was found to be positive when used in agriculture (mainly due to carbon sequestration), but negative when used as a fuel (mainly because air emissions from biochar production is not outweighed by lower emissions during use) [24]. In a study on rural Zambian conditions it was found that biochar amendment only resulted in positive overall environmental impacts when pyrolysis gas emissions are relatively low (such as in retort kilns or pyrolytic cook-stoves) and agricultural effects strong so that the negative impact of energy-intensive mineral fertilizers is spread out over more units of crop yield [25].

Even though the earlier LCAs performed point to benefits of both low production emissions and secondary benefits from fossil fuel substitution, different system boundaries makes it difficult to generalize between studies. In the present work we wished to compare various biochar generation technologies for rural condition on an equal basis. We did this for the above mentioned biochar technologies, with a special focus on comparing the novel flame curtain technology to the previously studied ones (earth-mound, retort, pyrolytic cook-stove) as well as to gasifiers. The study of flame curtain kilns is important since they have been implemented in 67 countries (http://www.ithaka-institut.org/en/ct/113-World-of-Kon-Tiki). Thus we carried out an LCA to compare the environmental burden or investment from production of biochar with the potential environmental benefits of carbon sequestration and/or heat generation from the pyrolysis utilized for cooking or electricity generation.

The goal of the work was thus not to further develop LCA techniques, but rather use it as a tool to compare various biochar production alternatives. The low middle-income context of Indonesia was taken as a case, but the trends are probably similar for most rural developing country situations. This comparison will aid in understanding the potential environmental impact of various technologies for biochar preparation under rural conditions in developing or lower-middle income countries where poorly maintained, artisanal technologies often prevail.

2. Materials and methods

2.1. Goal and scope

The goal of this LCA was to compare the environmental impact from the preparation of biochar under rural conditions in low-income or lower middle-income countries. Five different pyrolysis methods were compared, two low temperature technologies (i,ii) and three high-temperature technologies (iii, iv, v): (i) earth-mound non-retort earth mound kilns; (ii) retort kilns (Table S2), (iii) novel “Kon Tiki” flame curtain kilns, where both the all-steel deep cone variety and the simple soil pit variety were tested (Table 1); (iv) micro pyrolytic cook-stoves allowing the use of the gas flame energy for cooking purposes, and (v) gasifiers where the heat from the combustion of pyrolysis off-gases is utilized for electricity production (for further details, see SI). The functional unit was the preparation and sequestration of one kg biochar. All aggregated impact categories and their units are presented in Table 1.

2.2. System boundaries

Biochars produced by different technologies were compared by including the pyrolysis (biochar production) process, carbon sequestration and if applicable avoided electricity production or avoided wood combustion for cooking purposes in the system. The feedstock used to produce biochar was assumed to be a woody shrub or agricultural residue without any alternative value. No environmental effect from decomposition of feedstock was foreseen, assuming aerobic conditions and no stockpiling. We assumed no net emissions of carbon dioxide since the biogenic carbon uptake and release from the feedstock is taking place within approximately one growth season.

Avoided burden approaches were applied to include the electricity produced during biochar production using a gasifier, and the wood consumption avoided by cooking on a biochar-generating stove. In a rural location in a developing country the avoided source of electricity was assumed to be a house-hold sized diesel-fuelled generator (Tables S8–12). This also makes the data more universally applicable since the environmental effects of fabricating, transporting and combusting one litre of diesel are more constant than the environmental impacts of the electricity mix in one particular country. As this study focused entirely on biochar generation, the co-benefits of biochar, e.g. in agriculture or remediation, were outside its scope.

2.3. Inventory analysis

For earth-mound, retort and flame curtain kilns, primary data of gases emitted during pyrolysis were taken from measurements previously conducted in our projects in Zambia, Indonesia and Nepal [16,22] (Tables S4–6). Literature values and information from manufacturer were used for pyrolytic cook-stoves [19] and gasifiers (Tables S7–8).

Differences in biochar yield due to different technology

performance are included in the analysis since our functional unit was the preparation of one kg of biochar. We chose not to normalize to one kg of biochar-C since the carbon content of biochar is more dependent on feedstock than on pyrolysis method; especially rice husk has been observed to give low biochar C contents [26–30]. The biochar stability was estimated from literature H/C-ratios [31] for the different biochars (Table S3) and used to estimate the biochar stability and thus the amount of carbon sequestered over a 100-y perspective. Stabilities were estimated at 78% (earth-mound kilns), 77% (retort kilns) and 90% (flame curtain kilns, pyrolytic cook-stoves, gasifiers; Table S3), and this appears to correlate with the lower operation temperature being lower for earth-mound and retort kilns than for the other three kiln types. Even though biochar recalcitrance was earlier found to be mainly determined by production temperature [32], the potential total C sequestration (the product of recalcitrance and pyrolysis carbon yield) was observed to depend more on feedstock [32]. As our LCA concerned production technologies and not feedstock, this effect was considered to be outside the case boundaries. It should be noted though that uncertainty in the carbon stability numbers is introduced by i) the use of generic stability numbers per technology, as well as ii) the nonlinearity of the relationship between stability and H/C ratio.

Retort kilns need a certain amount of start-up wood to increase the temperature where exothermic pyrolysis can commence [16,17]. The amount of wood used was quantified to be 41± 14% of the mass of biochar generated in our previous field work (five different retort kilns [16]), or 15 ± 5% of the amount of feedstock (functional unit was one kg of biochar generated).

Other inventory data, mainly for kiln construction materials (e.g., steel and copper), were taken from the Ecoinvent 3.2 database [33] using processes from the allocation, recycled content model (excluding benefits from recycling). Capital goods were not included. The life cycle inventories for the modelled systems, along with literature references, are shown in the SI.

2.4. Life cycle impact assessment

To evaluate the environmental impact, the aggregated inventories were evaluated with the ReCipe life cycle impact assessment (LCIA) model [34]. The methodology is identical to previously conducted LCA analysis of biochar in rural areas [24,25,35] and is therefore only briefly described in the present paper.

Endpoint indicators using a hierarchist perspective, global normalization and average weighting set were chosen over midpoint indicators to allow comparison of effects caused by the different impact categories. Specific impact categories were given special attention (Table 1): i) climate change impacts for both ecosystems and human health due to GHG emissions; ii) emissions of particulate matter and their effect on human health trough inhalation, both on a regional and global level; iii) land transfer and occupation; iv) the cost of extraction of minerals and fossil fuels to highlight that the use of these resources cause changes in the effort to extract future resources (for details, see SI). The remaining less influential impact categories, such as e.g. ecotoxicity and eutrophication, are clustered into “remaining categories".

2.5. Sensitivity and uncertainties

Sensitivity analysis was conducted to address how important variations in input data would affect the results. This was conducted for two biochar stabilities over 100 y: 100% (complete stability, which is not realistic but useful for comparison purposes) and 13%. In a review of more than 100 mean residence times (MRT) for biochar in soil, the median MRT was around 300 y, and around 25% of the reviewed MRT values were below 100 y [36]. The 13% stability figure is the median of a recent meta-analysis showing a biochar half-life of as low as 34 years [37]. This figure is probably on the low side for the currently considered pyrolysis chars since it encompasses much less stable hydrothermal chars as well. However, we chose to use the value of 13% biochar stability in our sensitivity analysis as a published number on the low end of biochar stability.

The not yet realized heat exploitation for useful purposes (e.g. cooking, distillation, pasteurization, bread baking) from a flame curtain or retort kiln was also included in our sensitivity analysis. In trials with distillation of essential oils in Nepal, we observed that 24.5% of the heat could be used purposefully (unpublished data). Thus speculating that 25% of the pyrolysis heat is used purposefully [38], this implies avoided use of 0.49 and 0.80 kg firewood per kg biochar produced with the retort and flame curtain technologies, respectively (Tables S5 and S7). For other aspects including sensitivity in methods, previous studies of similar cases are referred to [24,25,35].

Uncertainties in the inventory data are shown as error bars in the figures and were estimated assigning standard deviations according to the Pedigree matrix method [39] and then calculated based on Monte Carlo simulations (n = 1000).

Table 1
Aggregated impact categories and their units from the ReCipe-model in emphasised impact categories used in this study.

Emphasized impact categories	Underlying categories	Unit
Climate change	Climate change effects on Human Health	Disability-adjusted life years (DALY) for human effect
	Climate change effects on Ecosystems	Species x year
Emission of particle matter	Particulate matter formation	DALY
Land transformation and occupation	Agricultural land occupation	Species x year
	Urban land occupation	Species x year
	Natural land transformation	Species x year
Mineral and fossil fuels	Metal depletion	U.S. dollars
	Fossil depletion	U.S. dollars
Remaining categories	Ozone depletion	Disability-adjusted life years (DALY) for human effect
	Human toxicity	Disability-adjusted life years (DALY) for human effect
	Photochemical oxidant formation	Disability-adjusted life years (DALY) for human effect
	Ionising radiation	Disability-adjusted life years (DALY) for human effect
	Terrestrial acidification	Species x year
	Freshwater eutrophication	Species x year
	Terrestrial ecotoxicity	Species x year
	Freshwater ecotoxicity	Species x year
	Marine ecotoxicity	Species x year

3. Results

Fig. 1 shows the production emissions (panel A), carbon sequestration (panel B) and if applicable avoided electricity production and wood consumption (panel C) connected to the preparation of one kg of biochar, as well as the total environmental impacts of these process categories (panel D). The various impact categories (climate change, particulate matter, land occupation, fossil fuels and remaining categories) were also summarized into one overall impact.

With regard to the *production emissions* category (Fig. 1 panel A), the most important negative environmental impacts stemmed from gas and aerosol emissions to air during pyrolysis and the impacts of producing the materials for the kilns. Pollutants (methane, carbon monoxide, non-methane volatile organic carbon, nitric oxides) and particulate matter released contribute to climate change and burden human health. Emissions from biochar production in earth-mound kilns present the highest potential environmental impact due to a high release of both pyrolysis gases and particulate matter (Table S4 and [15,16,25]). With regard to production emissions, gasifiers and retort kilns exhibited slightly more strongly negative potential impacts than pyrolytic cook-stoves and flame curtain kilns due to the embedded emission factors in the high mass of metal and concrete in their construction. In addition, higher production emissions for retort kilns result from the fact that retort kilns require an amount of start-up wood [16,17]. In some cases though, especially with very dry feedstock, the use of start-up wood can be avoided by using agricultural waste in the start-up chamber of the retort kiln, and the small bar in Fig. 1 under land transfer and occupation would disappear.

Pyrolytic cook-stoves performed best with regard to the particulate matter emission impact because of their relatively low PM_{10} emissions [20,40] compared to those for flame curtain and retort kilns [22] (Tables S5–S7). Gas emissions of a gasifier were assumed to be equal to those of a flame curtain pit (Table S8) because in both cases the pyrolysis gases are burned. In the case of gasifiers having lower gas emissions than flame curtain pits, the environmental effect of their gas emissions would be lower, and their potential overall environmental impact more positive.

The main difference with regard to life-cycle impacts between the all-steel "Kon Tiki" flame curtain kiln and the soil pit flame curtain kiln is the use of steel to construct the all-steel kiln (no materials are needed to construct the soil pit), as their gas and aerosol emissions were not significantly different [22]. It turned out, however, that the steel use in all-steel frame curtain kilns had a minimal negative impact on production emissions, because the approximately 100 kg of steel is divided over 10,000 kg of biochar generated during 100 runs (the conservatively assumed lifetime of an all-steel flame curtain kiln that can probably be run for up to 1000 times in three years). Similarly, the long life-expectancy of the gasifier diluted the impact of materials used for kiln construction per kg biochar produced.

Carbon sequestration provides a "win" (Fig. 1), i.e. a favourable environment impact. In Fig. 1 the stability of the biochars was derived from H/C ratios (Table S3). The difference in stability between earth-mound and retort kilns on the one hand (below 80% in a 100 y sequestration perspective) and the flame curtain kilns, gasifiers and TLUDs on the other hand (around 90% stability over 100 y) resulted in slight differences in carbon sequestration (Fig. 1, panel B). The importance of carbon sequestration for the overall impact of biochar generation was earlier shown for an LCA on biochar for corn and forest residue in Canada, where a reduction in GHG emissions was mainly due to the stabilized carbon in the biochar [41]. The reductions in emissions attributable to soil C sequestration were greater for corn fodder than for forest residue [41].

The *avoided processes* category only concerned pyrolytic cook-stoves and gasifiers, where wood consumption and electricity use are avoided, respectively. Avoiding wood consumption by cooking on pyrolytic cook-stoves run on agricultural waste led to favourable impacts on climate change (avoided carbon emissions due to deforestation), particulate matter emissions (due to cleaner cooking) and especially land transfer and occupation (due to reduced loss of biodiversity measured in species loss per year) (Fig. 1, panel C). In the case of our example of rural Indonesia, the use of a gasification unit reduces the need for electricity generation via off-grid diesel generators, which is strongly beneficial in terms of climate change (avoided carbon emissions), particulate matter emissions (from diesel combustion) and fossil fuel use (Fig. 1 panel C). On the other hand in villages the generator is only employed when electricity is needed while the gasifier would have to be employed all day round to produce electricity when needed. In addition if the gasifier is not used during the night batteries might be necessary with associated production impact. Thus the presented data are probably an "ideal" case for gasifier implementation.

The kilns considered would most likely be used with harvest residues that otherwise would rot in the fields or be burned in the field producing emissions of methane, CO and CO_2 [42]. Replacing field harvest residue combustion or rotting with charring these feedstocks would render more positive potential environmental impacts [42] but was left outside the boundaries of the current analysis due to uncertainties in the avoided emissions.

4. Discussion

The *total environmental impact* for the flame curtain kilns was shown to be lower than that of both earth-mound kilns and retort kilns but still not significantly beneficial for the environment despite relatively low gas/aerosol emissions and resource use, as well as no need for start-up wood (Fig. 1 panel D). Thus, making biochar from both types of flame curtain kilns was observed to be more or less environmentally neutral in a life-cycle perspective, as production emissions were compensated for by the positive potential effect of carbon sequestration. Flame curtain kilns turned out to be slightly better than retort kilns because of the lower material use and the avoidance of start-up wood (Fig. 1 panel D). Flame curtain kilns exhibited lower CO emissions than retort kilns [22], however, this only led to minor life-cycle impacts as the emissions of PM_{10} and methane were similar for retort and flame curtain kilns [22], and the impact of the latter two emissions exceed those of CO in the LCIA applied. Thus, co-benefits in the form of soil restoration and increased plant growth are needed to warrant the implementation of flame curtain kilns in a life-cycle perspective. Such agricultural effects in a rural low-income context were evaluated in an extensive LCA in our previous work on biochar in Zambian smallholder agriculture [25].

Flame curtain kilns are in addition cost-effective, faster and easier to operate than other biochar production methods. In those places where simple soil pit flame curtain kilns can be made easily, they can provide a cost-effective and environmentally neutral alternative for biochar generation. In those cases where this is not possible (rocky surface, waterlogged conditions) all-steel flame curtain kilns provide an environmentally almost equal but more costly alternative. The use of the waste heat of flame curtain kilns would make the overall environmental impact positive; the construction of cheap and easy to handle heat recovery devices should therefore be fostered. Novel elements of the present study included i) evaluation of the novel flame curtain kilns in an LCA; ii) inclusion of the avoided impacts of deforestation for cook-stoves; iii)

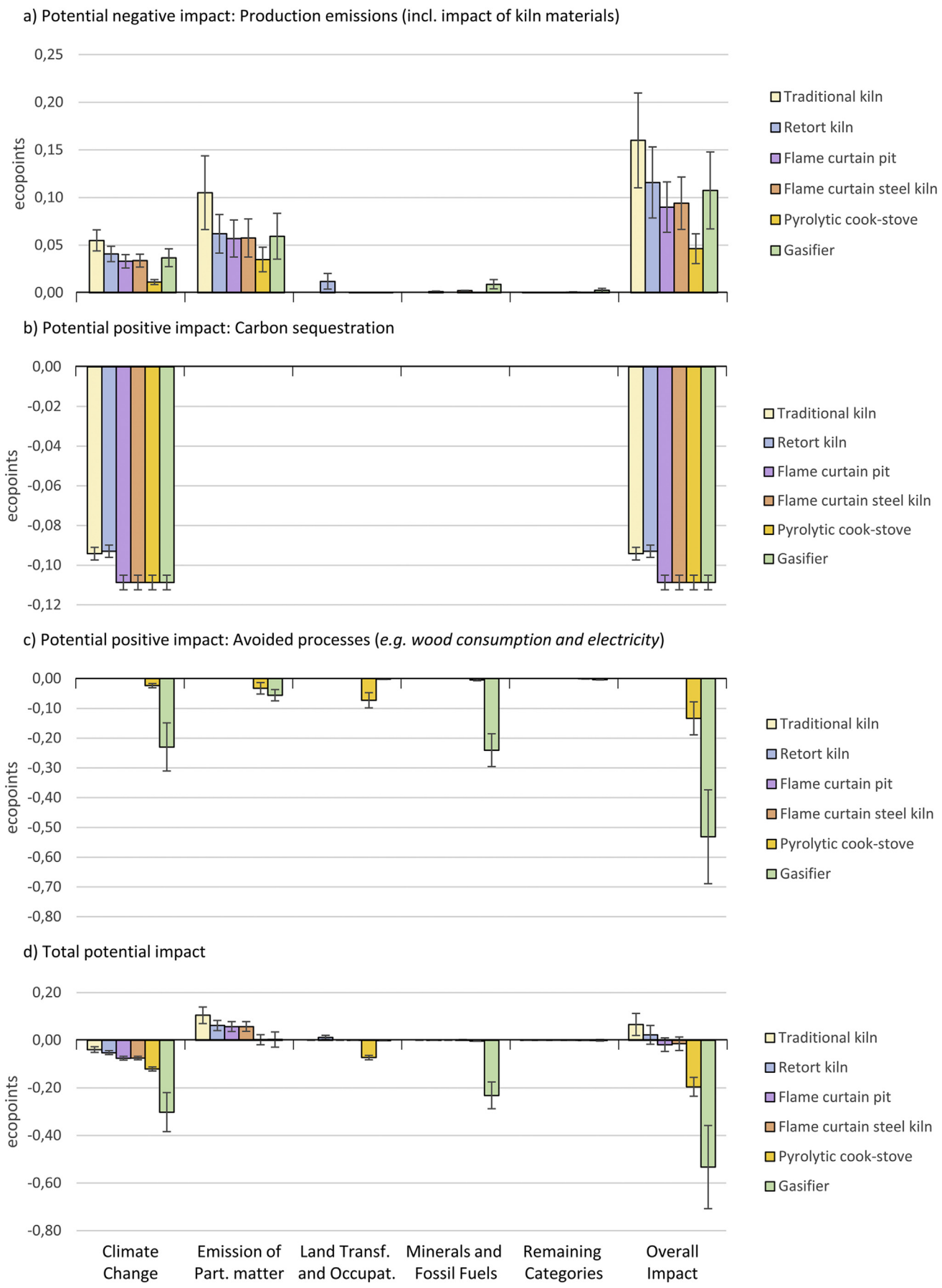

Fig. 1. Normalized impacts (ecopoints) from a) production emissions (inclusive the impact of kiln materials), b) carbon sequestration, c) avoided processes (wood consumption and electricity for the cook-stove and gasifier, respectively), and d) total environmental impact. Positive values indicate negative environmental impact whereas negative values show avoided impacts (improvement). The error bars show standard deviations based on Monte Carlo simulations. Axis scale similar in all panels for comparison purposes.

Fig. 2. Normalized impacts (ecopoints) from (a) the sensitivity analysis of biochar stabilities at 13%, as calculated from H/C-ratio (Table S4) and 100%, and (b,c,d) the effect of the difference in stability for the total environmental impact from the production of one kilo biochar. Positive values indicate negative environmental impact whereas negative values show avoided impacts (improvement). The error bars show standard deviations based on Monte Carlo simulations.

comparison of simple technologies to gasifiers in a low-income rural setting; iv) inclusion of the avoided impacts of electricity generation for gasifiers; v) inclusion of a low (13%) biochar stability of the in the sensitivity analysis, and vi) inclusion of heat utilization of medium-scale low-technology pyrolysis techniques in the sensitivity analysis.

The total environmental impact was significantly favourable for gasifier units and pyrolytic cook-stoves, as a result of the avoided processes of wood consumption and electricity generation. Importantly, these secondary avoided process impacts overwhelmed the primary impacts of biochar production itself, and warrant their use in an overall environmental perspective even if no additional benefits from the biochar are gained. The observation that avoided emissions from electricity generation by gasifiers results in environmental benefits is in accordance with earlier observations in an LCA on biochar and bioenergy generation slow pyrolysis, fast pyrolysis and gasification of ten biodegradable residues [23]. It is also confirmed by a study comparing four potential gasification technologies to obtain rice-straw based energy, where all technologies were found to result in a positive potential energy benefit [43]. Another LCA study found that pyrolysis gasoline from pyrolysis oil has lower environmental impacts than petroleum gasoline, but that it is challenging to find the optimal balance between pyrolysis oil and biochar generation. The reasons were that the fractions of bio-oil and biochar generated are dependent on pyrolysis conditions, and that biochar characteristics and agronomic and C sequestration effects are uncertain [44].

An LCA study on rice residue management in Vietnam compared residue burning to biochar generation by pyrolytic cook-stoves that also produced heat energy for cooking. It was assumed to take eight years to produce enough biochar for optimal agronomic effects, but after this time biochar addition reduced the carbon footprint of rice cropping by over 40% [45].

For rural low-income situations implementation challenges not encompassed by the LCA exist for clean stoves and gasifiers. For cook-stoves this is due to the small amounts of biochar generated and the amount of labour involved in making appropriate amounts of biochar. Cook-stoves are probably most suitable for biochar generation for small kitchen gardens [46]. For gasifiers the main challenge is their high investment cost and labour insensitivity reducing their plausibility in many rural areas. In addition, solar-powered off-grid solutions will often provide a more attractive option for electrification [47].

In contrast to the other kilns, biochar production with earth-mound kilns provided a significantly negative potential environmental impact, because the production emissions (Fig. 1 panel A) are so high that they are not compensated by carbon sequestration (Fig. 1 panel B). Thus the use of earth-mound kilns for making biochar cannot be advocated unless significant additional benefits are obtained by its use in agriculture. This could for example be a reduction in the use of energy-intensive mineral fertilizers [25].

Sensitivity analyses. Because of the wide range in stability of biochars, we carried out a sensitivity analysis with regard to carbon stability, assuming three stabilities: i) 13% [37], ii) stability in accordance with H/C-ratio (77–90%), and iii) 100% stability over 100 y (Fig. 2a). Biochar stabilities of 77% to 90% resulted in a positive environmental impact similar in quantity to the negative impact from production (overall impact of retort and flame curtain kilns; Fig. 2), while a stability of 13% provided a far lower win than burden for all kilns except TLUD and gasifier (Fig. 2b). For the flame curtain kilns, an unrealistic biochar stability of almost 100% is needed to obtain beneficial potential environmental effects of biochar

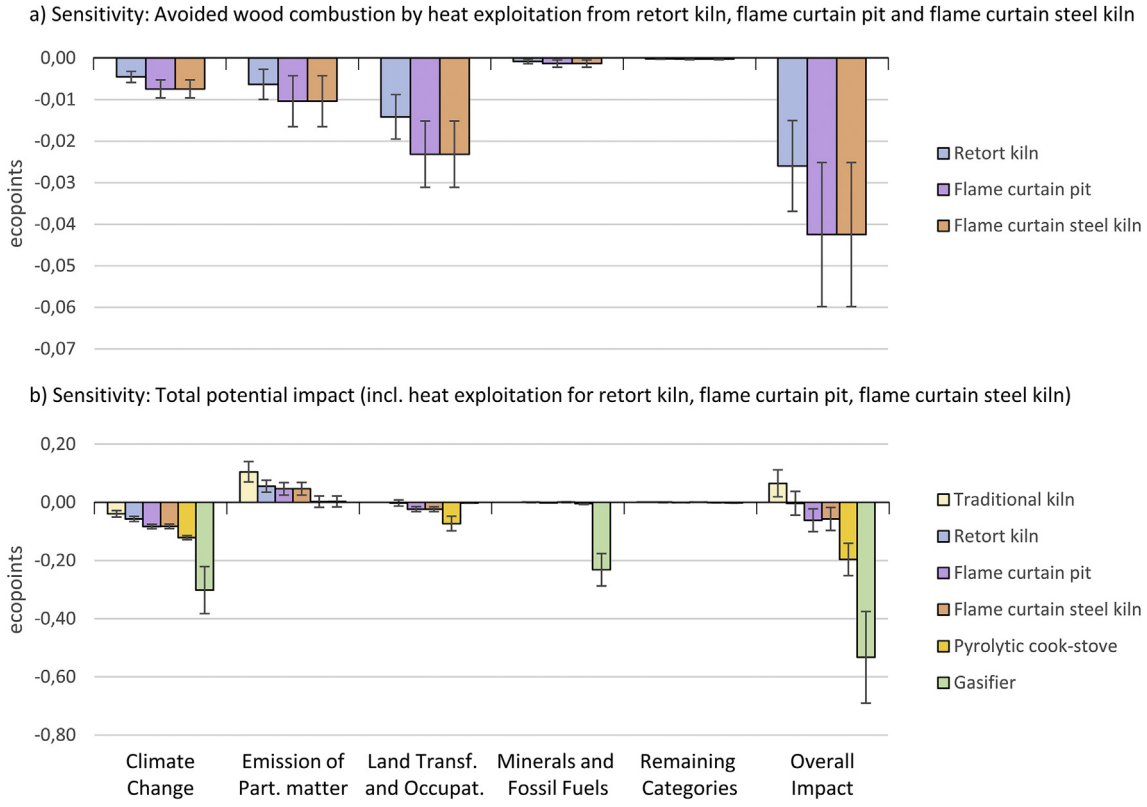

Fig. 3. Normalized impacts (ecopoints) from a) the sensitivity analysis of exploitation of heat (25%) from biochar production with flame curtain pit, flame curtain steel kiln or retort kiln, and b) the effect on the total environmental impact from the production of one kilo when heat is exploited. Positive values indicate negative environmental impact whereas negative values show avoided impacts (improvement). The error bars show standard deviations based on Monte Carlo simulations.

generation alone (Fig. 2d).

If heat could be exploited for useful purposes (e.g. cooking, distillation, pasteurization, bread baking) from a flame curtain or retort kiln the avoided use of fire wood for these secondary processes would improve the environmental impact of the technology [8,22]. This practice is in an early phase and was therefore only included in our sensitivity analysis (Fig. 3). This potential additional positive effect would render the total environmental impact of biochar production alone with the flame curtain positive for the environment (Fig. 3b). For the retort kilns this was not the case as the production emissions were too extensive to overcome (Fig. 3b), mainly because of the high aerosol and methane emissions.

Biochar characteristics (both related to stability and soil restoration) vary between lower-temperature biochars (earth-mound and retort kilns) and higher-temperature ones (flame curtain kilns, cook-stoves and gasifiers), and between the ash-rich gasifier biochars [29,30] and the ones made by other kilns. Apart from stability issues mentioned above, this will also influence the effectiveness of biochar in an agricultural or soil pollution remediation perspective [30]. Consequential impacts of these differences were outside the scope of the present work, but should be included in LCAs of various alternatives for full-value chain biochar scenarios.

5. Conclusion

In conclusion, flame curtain kilns showed more positive potential environmental impacts than traditional earth-mound and retort kilns due to their smaller production emissions. In the whole life cycle perspective, the generation of biochar in cook-stoves or gasifiers was observed to provide the most beneficial alternative due to avoided impacts.

The use of earth-mound kilns should not be advocated. Even though they do not require any material or investment, they are slow, laborious and negative potential impacts for the environment.

Importantly, biochar generation *per se* does not result in significantly positive life-cycle impacts for flame curtain and retort kilns, and thus additional environmental benefits are needed to warrant their generation in a life cycle perspective. The most important such benefits are probably waste water treatment and increased soil fertility.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2017.04.001.

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