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Environmental and economic impacts of biochar production and agricultural use in six developing and middle-income countries

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1. Introduction

The environmental performance of biochar production and agricultural use, as quantified using life cycle assessment (LCA), can vary geographically due to differences in biochar production method, which influence the resources used and emissions resulting from processes included in the biochar life cycle (Owsianiak et al. 2018a, b). Differences in soil quality and agronomic effectiveness of biochar will also influence environmental benefits. Similarly, economic costs and benefits of biochar production methods can show strong variations, depending on the costs associated with installation and operation in relation to economic benefits arising from increased crop productivity following application to soil (Dickinson et al. 2015).

LCA studies most often report that the use of biochar is expected to bring environmental benefits, while economic analyses generally indicate that feasibility of biochar use in agriculture may be jeopardized by high labour costs and limited effects on crop yield following biochar application to soil (e.g. Bach et al. 2016; Roberts et al. 2010). In underdeveloped rural areas of low-income countries, the positive agricultural effect of biochar addition to the poor and often unproductive soils found in these areas, often carries the greatest economic impact (Robb et al. 2020, Martinsen et al. 2014). In middle-income countries, labor and other costs are higher and increased crop yield may be achieved by alternative technical agricultural innovations. It is therefore important to evaluate trade-offs between various biochar production techniques and alternative uses of the biowaste. In addition, both environmental and economic tradeoffs should be investigated before the use of biochar in agriculture is advocated (Roberts et al., 2010), especially as the income of a country increases. Majmunder et al. (2019) investigated the environmental and economic benefits of applying crop residue compared to biochar produced from the crop residues to soils and the potential implications for soil carbon sequestration. Results demonstrated that converting crop residues to biochar can be an efficient method to sequester soil carbon, but that clear cost-effectiveness is not always demonstrated. Dickinson et al. (2015) showed that economic performance of biochar production and use in cereal agriculture varied significantly between Sub-Saharan Africa and North-Western Europe, mainly due to differences in agricultural benefits from biochar application and costs of the pyrolysis process used to produce the biochar. It is therefore very important that both economic and environmental impacts are considered as they depend on the location of the biochar implementation. Studies quantifying these trade-offs are, however, scarce. Sparrevik et al. (2014) reported that positive environmental effects of carbon sequestration and the economic benefits arising from increased agricultural production outweighed other negative environmental impacts (e.g. health effects) when biochar was produced and used in Indonesia. Field et al. (2013) investigated economic and environmental factors for a case study in Colorado, USA. Results suggested that financial returns are generally greater when biowaste is consumed for energy (biocoal) than when added to agricultural soils.

To date, there are no studies that systematically investigate both environmental and economic performance of biochar use in agriculture for both developing and middle-income countries (Matuštík et al. 2020). To address this important gap, environmental and economic life cycle impacts of biochar production and agricultural use in six developing and middle-income countries are quantified and compared here. The comparison was framed around two biochar production methods (flame curtain kiln and a large-scale gasifier) and two alternative biowaste management strategies (home composting and windrow composting).

2. Methods

2.1. Scenarios

Environmental and economic impacts of biochar production and agricultural use in Ethiopia, Indonesia, Kenya, Peru, Vietnam, and China were modelled in this study. These countries were chosen as they represent six countries with varying incomes, varying farmer practice, and are those in which biochar has been piloted in the "Biochar for Sustainable Soils" (B4SS) project, thus its integration with normal farmer practice can be considered possible. The overall development goal of the B4SS project was to demonstrate and promote the adoption of Sustainable Land Management practices involving the use of innovative organic amendments, based on biochar (Braby 2019). The B4SS project selected these six particular countries to build on the foundations laid by previous interventions and scientific field trials evaluating diverse formulations and application rates of biochar for different scenarios for soil types, climates and agricultural systems.

A distinction was made between biochar production in agricultural areas (with lower income in a particular country), and biochar production in more urbanized areas (with higher income). In the former a flame curtain kiln was chosen as a simple and cost-effective technology for biochar production (Cornelissen et al. 2016) and in the latter a more advanced biochar production method based on gasification (with replacement of electricity from the grid) was modelled (Smebye et al. 2017; Peters et al. 2015). The flame curtain kiln is a promising technology for direct implementation in rural areas of developing and middle-income countries, as it combines the simplicity of a traditional kiln with the low emissions of more advanced systems (retort kilns), avoids the use of external fuel for start-up, is low-cost (only labor to dig a soil pit is required), fast (3 to 5 hours), and relatively easy to operate (Cornelissen et al. 2016). It has been applied in over 70 countries (Schmidt and Taylor, 2014). The environmental impact over the whole life cycle were compared with home composting (in rural areas) or windrow composting (in urbanized areas) as these are common current management options for biowaste in those countries. Biochar production using flame curtain kilns will compete with home composting, which is currently becoming an important diversification route for treatment of organic waste in rural areas (Lleó et al. 2013). In urban areas, where volumes of biochar feedstock are larger and more centralized, biochar production using a more advanced gasifier system is a realistic scenario. This gasifier system will compete with windrow composting, which is a commonly used system for the management of larger volumes of waste (Bong et al. 2017). In windrow composting, biomass is allowed to degrade in somewhat more controlled conditions when compared to home composting, as it is piled in long rows (windrows) and regularly turned to improve porosity, oxygen content, and control moisture and heat exchange (Andersen 2010). The use of six countries, two biowaste management scenarios (pyrolysis and composting) and a comparison of flame curtains kilns with home composting and gasifiers with windrow composting gives a total of 24 scenarios, see Table 1. Other biochar production technologies, like retort kilns, could also be considered, but they were not included as the study focused on the end economic points (i.e. cheap and expensive). However, it would be expected that they would perform better economically than high-cost gasifier, but worse than simple low-cost kilns.

Table 1. Overview of the assessed scenarios for management of biowaste in developing and middle-income countries.

Country area	Biowaste system	Technology	Product(s)	Geographic location [a]	# Scenario
Rural	Pyrolysis	Flame curtain kiln	Biochar used as soil conditioner in agriculture	CN; ET; ID; KE; PE; VN	1-6 [b]
	Composting	Home composting	Compost replacing inorganic fertilizers	CN; ET; ID; KE; PE; VN	7-12 [c]

Urban	Pyrolysis	Gasifier	Biochar used as soil conditioner in agriculture; electricity replacing electricity from the grid	CN; ET; ID; KE; PE; VN	13-18
	Composting	Windrow composting	Compost replacing inorganic fertilizers	CN; ET; ID; KE; PE; VN	19-24

[a] ISO country codes: China (CN); Ethiopia (ET); Indonesia (ID); Kenya (KE); Peru (PE); and Vietnam (VN)

[b] Country differentiation was not made across ET, ID, KE and VN for the environmental assessment of pyrolysis using flame curtain kiln

[c] Country differentiation was not made for the environmental assessment of home composting.

2.2. Criteria for data selection

Two criteria were used when choosing data for both LCA and economic analysis: (1) a parameter value must (ideally) be representative of the technology considered in the study, and (2) a parameter value must (ideally) be country-specific, if relevant. Hence, in the LCA only data previously reported for biochar production using flame curtain, gasifier, home composting and windrow composting systems was used. For the LCA, geographic differentiation of parameters used to construct life cycle inventories was carried out at three levels: (i) electricity grid mixes, where country-specific mixes were used (Table S4); (ii) maize grain production, in the underlying process of water irrigation where country specific electricity mix was used for China and Peru (irrigation is not used in the remaining countries); and (iii) crop yield increases, where a 14% increase for China (being the average from tropical and temperate regions) deviated from the 25% increase used in the remaining (tropical) countries (Jeffery et al. 2011, 2017). Note, that for several LCA-related data, the second criterion was either not relevant (e.g. emissions of greenhouse gases) or could not be met due to lack of country specific data. Thus, there was no country differentiation for the flame curtain kiln scenarios for Ethiopia, Indonesia, Kenya and Vietnam, where biochar effects and agricultural practices were assumed the same (details are given in Section 2.2.2.) Further, no country differentiation was made for the environmental assessment of home composting because of a lack of country-specific inventories for this system (e.g. greenhouse gas emissions are assumed independent of the location). Therefore, in total 16 scenarios were modelled in the LCA. For the economic analysis, nearly all data were technology- and country-specific. In a few cases, data from countries of similar development status were used (e.g. price of fertilizer in Ethiopia assumed equal to that of Kenya). Sources of all data used in the LCA and in the economic analysis are provided in sections “2.3.3. Model parameters and unit processes” and “2.4.2. Data sources and assumption”, and in the Supporting Information (Tables S1-S6 and S16).

2.3. Life cycle assessment of management of biowaste

The LCA was conducted in accordance with the requirements of the ISO 14044 standard and the guidelines of the EU Commission’s ILCD Handbook (ISO, 2006; EC-JRC, 2010), combined with specific recommendations for LCA applied to waste management systems (Laurent et al. 2015).

2.3.1. Functional unit

The primary function of biochar production systems in the context of this study is to convert carbon present in biowaste into biochar used as a soil conditioner with a carbon storage value. The functional unit was therefore defined as the “management of 1 kg of wet biowaste in middle-income and developing countries”. This functional unit was chosen as it allows a consistent comparison with composting (home or windrow) as biowaste treatment strategy. The secondary functions; increase in crop productivity when biochar is applied to soil and provision of electricity from the gasifier were considered in the study. It was assumed that the water content and biowaste composition were the same for all six countries.

2.3.2. Modelling framework and system boundaries

Biochar production and use in agriculture is a relatively new technology and its implementation is not expected to cause large scale market consequences (for example the need to install new power plants, etc.). Therefore, consistent with ILCD's recommendations, the current LCA is considered a microlevel decision support situation (type A) (EC, 2010). This implies that: (i) system expansion is the preferred way to solve multifunctionality, and (ii) average processes are to be used to model the background system of the study. There are several practical implications of these two methodological choices. First, crediting via impact offsets to replaced or avoided processes was carried out (Bjørn et al., 2018). Second, energy produced in the gasifier scenarios was used to replace electricity from the grid according to the current grid mix in the respective countries. Third, home and windrow compost were assumed to replace nitrogen, phosphorus and potassium (NPK) fertilizers produced using a global market average. Fourth, impact offset to account for increasing crop productivity was given using average processes for maize agriculture in the respective countries. In contrast to earlier studies, impact offsets were not given for avoided incumbent waste treatment (Owsianiak et al. 2016; 2018). This is because the functional unit used here allows a direct comparison of environmental impacts from the biochar systems with those of composting systems. An overview of system boundaries specifying the processes included in the LCA is presented in Fig. 1.

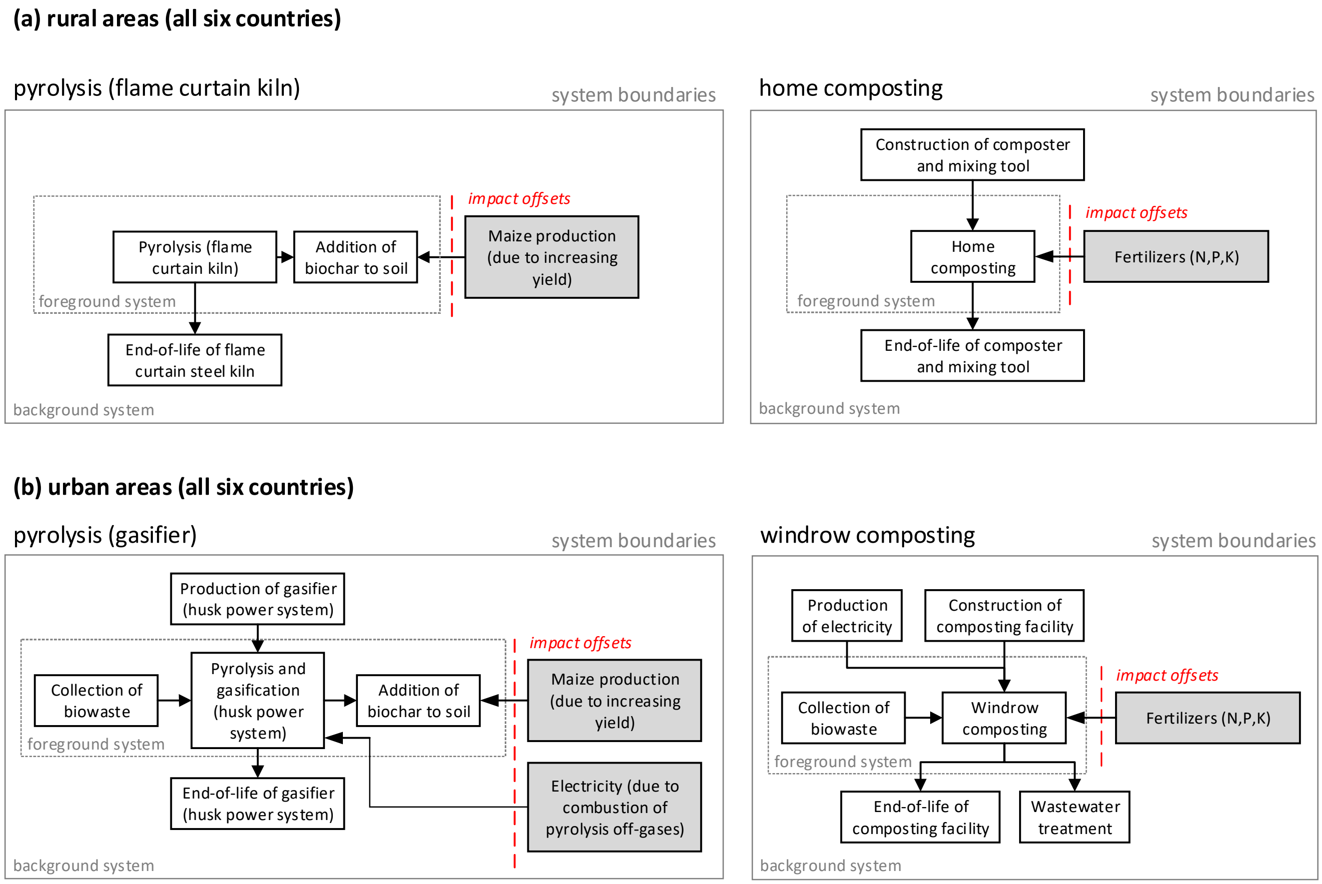


Fig. 1. System boundaries for the functional unit "management of 1 kg of wet biowaste in urban middle-income and developing countries" in (a) rural areas in all six countries, where comparison is made between pyrolysis using flame curtain kiln and home composting, and (b) urban areas in all six countries, where comparison is made between pyrolysis using gasified and windrow composting. All countries are modelled with a rural and urban setting. Grey boxes indicate avoided processes.

2.3.3. Model parameters and unit processes

Model parameters for the foreground system were based on measurements and literature data and are shown in Section S1 of the SI. Briefly, data related to the production of the flame curtain kiln and the gasifier and emissions from pyrolysis and pyrolysis/gasification units were based on measurements reported in Smebye et al. (2017). Effects of biochar on crop yield are based on meta-analyses carried out for tropical and temperate regions (where average crop yield increases by 10 and 25%, respectively), when compared to yields without biochar addition (Jeffery et al. 2011, 2017). These yields were also used irrespective of whether the soil had previously been treated with biochar. Data on biochar stability in soil are based on measurements by Zimmerman and Gao (2013) carried out for six biochars spanning a relatively wide range of mineralization kinetics. Concentrations of nutrients (N, P, K) in the biochar are based on Ippolito et al. (2015) (Table S3). Greenhouse gas (GHG) emission factors for home composting and windrow composting are taken from the literature (see Tables S5 and S6).

Unit processes used in the foreground system are reported in Section S2 of the SI. Unit processes for the background system are those available in the Ecoinvent database, version 3.3 (Wernet et al. 2016). Ecoinvent does not contain country-specific unit processes for low voltage electricity production in Ethiopia, Kenya or Vietnam and these had to be constructed by using country-specific grid mixes and power generation processes taken from countries of similar development status and the same continent (Zambia in case of Ethiopia and Kenya, and Thailand in case of Vietnam). Likewise, generic Ecoinvent processes for maize agriculture and irrigation were adapted to construct country-specific processes by making selected flows (water use and electricity input) country-specific. Section S2 of the SI presents details of these adaptations. The product systems were modelled in SimaPro, version 8.3.0.0 (PRé Consultants B.V., the Netherlands).

2.3.4. Life cycle impact assessment

ReCiPe 2016, version 1.0 as acquired from PRé (CSV Format version: 8.0.5) and imported into SimaPro was used as impact methodology (Huijbregts et al. 2016). This methodology was chosen because it allows environmental impact scores to be calculated at endpoint (damage) levels consistently for all impact categories. Impact scores were calculated using global characterization factors for the default, hierarchist perspective. All 21 ReCiPe's impact categories were considered. Normalization and weighting of characterized life cycle impact assessment results was not deemed necessary because: (1) according to ISO standards, weighting shall not be applied in the context of comparative assertions, like those reported in the current study, and (2) impact scores were calculated at damage level, which enables their direct comparison without the use of weighting factors.

2.3.5. Inventory uncertainties

Uncertainties in the life cycle inventories for the foreground processes (e.g., in material inputs or emissions) were mainly estimated using the Pedigree matrix approach (Ciroth, 2013). Uncertainties in GHG emissions from home and windrow composting were defined such that 95% of the values of a GHG emission were within an uncertainty factor k from the median of a lognormal distribution (Huijbregts et al. 2003). Uncertainties in the background processes were based on geometric standard deviations already assigned to flows in the Ecoinvent processes that were used to create the background system. Monte Carlo simulations (1,000 iterations) were carried out for pairwise comparisons between selected scenarios listed in Table 1 while keeping track of the correlations between the two systems. Comparisons were considered statistically significant if at least 95% of all 1000 Monte Carlo runs were favorable for one scenario.

2.4 Economic analysis of management of biowaste

2.4.1. Assessment methodology

A generic, simplified economic analysis from the individual decision-maker's (household/farmer or company) point of view was performed to assess economic performance of biochar systems. The main market costs and benefits associated with the two pairs of urban and rural systems a)-b) in Figure 1 were quantified for each country.

In order to make the economic assessment as consistent with the environmental assessment as possible, the costs and revenues (benefits) were calculated for the same functional unit: treatment of 1 kg wet biomass in developing and middle-income countries. Net profit or benefit (or loss) was defined as follows (Dickinson et al. 2015; Boshir et al. 2016):

(1) Net profit (loss) = $R - C_{CT} + C_P (L, K) + C_A$

where

R = Revenue (benefit) of replacing fertilizer, electricity and/or maize production.

C_{CT} = Collection and treatment (drying) costs of wet waste biomass.

C_P (L, K) = Labour (L) and capital investment (K) costs associated with each of the processes (P) pyrolysis via gasification or flame curtain kiln (biochar production) or composting at home or windrow composting.

C_A = Costs of transport and application of biochar and composted waste.

Economic and environmental analyses normally treat the effect of time differently (e.g. Huysegoms et al. 2018). For simplicity, the environmental impacts used as basis for the economic analysis were assumed to be realized within one year, meaning that discounting costs and revenues could generally be ignored, except in the case of capital costs, which were annualized using assumptions of technical lifetime and discount rate (Dickinson et al. 2015). In the cases investigated here, this assumption is not important in practice, since non-market effects such as climate and ecotoxicity, which are usually time integrated over very long time horizons (that is, 100 years for climate and infinite for ecotoxicity) in the environmental assessment, are not considered in the economic assessment. One implication of this simplification is that the biochar effect on soil is conservatively assumed to last for one year (or agricultural cycle). In cases where the effects are felt more long term, results will be more favorable. Further, for simplicity a linear cost function, i.e. no economies of scale, was assumed when converting figures to USD per kg waste. Finally, capital investments in new buildings were not considered. This corresponds with the process-based LCA, where such investments are generally not considered.

2.4.2. Data sources and assumptions

End-of-life costs of each system were assumed to be negligible and set to zero. Where possible, costs and revenues were quantified based on individual country data for wages and prices, though detailed, comparable statistics are often scarce (Dickinson et al. 2015). Assumptions and estimates were made based on field experience from the countries obtained through the B4SS project, and/or from literature and statistical sources (see SI Section 3 for details).

Revenues (benefits), R, were calculated for each process using the physical unit change (electricity in kwh, kg maize or fertilizer) from the environmental analysis multiplied by respective domestic prices from the most recent year available and adjusted by country inflation rates to 2019.

Waste collection and treatment costs, C_{CT}, were calculated based on estimates of collection and drying times per ton of cocoa waste for Indonesia (Sparrevik et al. 2014), multiplied with, domestic inflation-adjusted hourly wages (opportunity cost of labor) for the latest available year for the manufacturing sector, mainly based on statistics from the International Labour Organization (ILO). For simplicity, no differentiation was made in collection and treatment costs between rural and more urban areas within countries.

The capital and operating costs, C_P (L, K), and biochar and/or compost application costs, C_A, were estimated in the following ways for each of the respective processes:

(a) Pyrolysis through flame curtain kiln: The estimate presented by Pandit et al. (2018) of USD 144 per ton biochar including labor, packaging, storage and transportation based on freely available biomass and using a flame curtain kiln was used. To differentiate this figure between countries and since labor is only part of this cost, the figure was scaled based on most recent GDP/capita figures.

(b) Home composting: Home composting was assumed to be a simple work process where biowaste is sorted with a simple mixing tool, and then added to the soil thus replacing fertilizer use. The labor time assumed was half that of collecting the waste biomass above.

(c) Pyrolysis through gasification: The investment cost (including transport and civil works) of approximately USD 120 000 and annual operating and maintenance cost of around 10 per cent of the investment cost for the type of gasifier specified in Smebye et al. (2017) was taken from an investment analysis carried out for Uganda by experienced researchers at Norges Vel, Norway (SI Section 3). Since gasifiers are produced and delivered on the international market, investment cost between countries were not differentiated. The investment cost was then annualized, as described above, in this case assuming a technical lifetime of 10 years and a 10 per cent discount rate. The annual maintenance costs were divided equally as parts bought from the international market and labor costs, differentiated between countries using GDP/capita. The gasifier was conservatively assumed to produce around 6 tons of biochar per year

(60 tons biowaste capacity), with the given electricity output (see Section S3). In all cases, it was assumed that the gasifiers substituted electricity from the national grid giving an electricity revenue equivalent with national grid electricity prices.

(d) Windrow composting: This process is more advanced than home composting and involves using some form of compost facility requiring some capital costs and labor. There is limited information about such systems in the published literature. An investment cost of USD 20 000 for land, facilities and equipment was used based on estimates from two relatively small-scale composting systems in Indonesia and Sri Lanka analyzed (Pandyaswargo and Premakumara 2014). This cost was assumed to be constant between countries and a technical lifetime of 20 years was assumed in order to annualize costs. The monthly labor costs for a daily production of 0.3 tons of compost was set to USD 186, based on estimates in Pandyaswargo and Premakumara (2014), and differentiated between countries using relative wage rates.

Finally, for $\mathbf{C_A}$, costs of transport and application of biochar and composted waste to the soil, were estimated according to Dickinson et al. (2015) for Sub-Saharan Africa. One man-day for transport per ton of biochar and two man-days per ton for application were assumed and used for both biochar and (windrow and home) compost.

3. Results and discussion

Figure 2 shows the results of the environmental analysis at the damage level, representing the median of 1,000 Monte Carlo runs. The results are shown for all scenarios presented in Table 1 (16 in total, given that country differentiation was not considered for the six home composting scenarios and no differentiation was made between four countries in the flame curtain kiln scenarios). The corresponding (absolute) uncertainties, together with results for all individual impact categories, are presented in the SI, Section S4. Figure 3 shows the results of the economic analysis, comparing the key components of costs (negative domain in the chart) and revenues (positive domain of the chart). Overall, the environmental and economic results show several trends, detailed below.

3.1. Biochar use in agriculture brings net environmental benefits

Irrespective of the scenario, all pyrolysis treatment options bring environmental benefits, as is illustrated by net negative impact scores in Figure 2. Indeed, benefits from replaced electricity or increasing crop yields, combined with benefits from long-term carbon storage when biochar is added into soil, outweigh the environmental burden associated with biochar production. The negative effects from the production of biochar using the flame curtain kiln are mainly due to emissions of methane from the kiln. Benefits stem from avoided extraction of water for maize irrigation (China and Peru only) and avoided emissions of sulphur dioxide and CO_2 when maize straw and whole-plants are dried (all countries). Earlier assessments of the environmental performance of biochar systems in a life cycle perspective have largely focused on greenhouse gas emissions and related contributions to climate change mitigation (e.g. Roberts et al. 2010; Woolf et al. 2010; Peters et al. 2015; Tisserant and Cherubini 2019 and references therein). These previous studies have shown benefits from temporary carbon storage and/or increased crop yields. The results of this study corroborate these previous LCA studies as they show that pyrolysis is expected to bring environmental benefits (with biochar used in agriculture) in cases where other relevant stressors, besides climate forcers, are considered.

3.2 Gasification performs better than flame curtain pyrolysis

Results show that the gasifier scenarios bring consistently larger environmental benefits per functional unit when compared to flame curtain kiln scenarios. Net environmental impacts for gasifier scenarios are on average (across countries) one order of magnitude smaller when compared to the flame curtain kiln scenarios (for damages on ecosystems, human health, and resources, respectively). As explained in Smebye et al. (2017), these additional benefits arise from the replacement of electricity from the current grid mix with electricity from the gasifier. In practice, this means that the impacts from local power production in gasifiers are smaller compared to the electricity produced from the grid in all the studied countries irrespectively of the amount of renewable energy used in the energy mix.

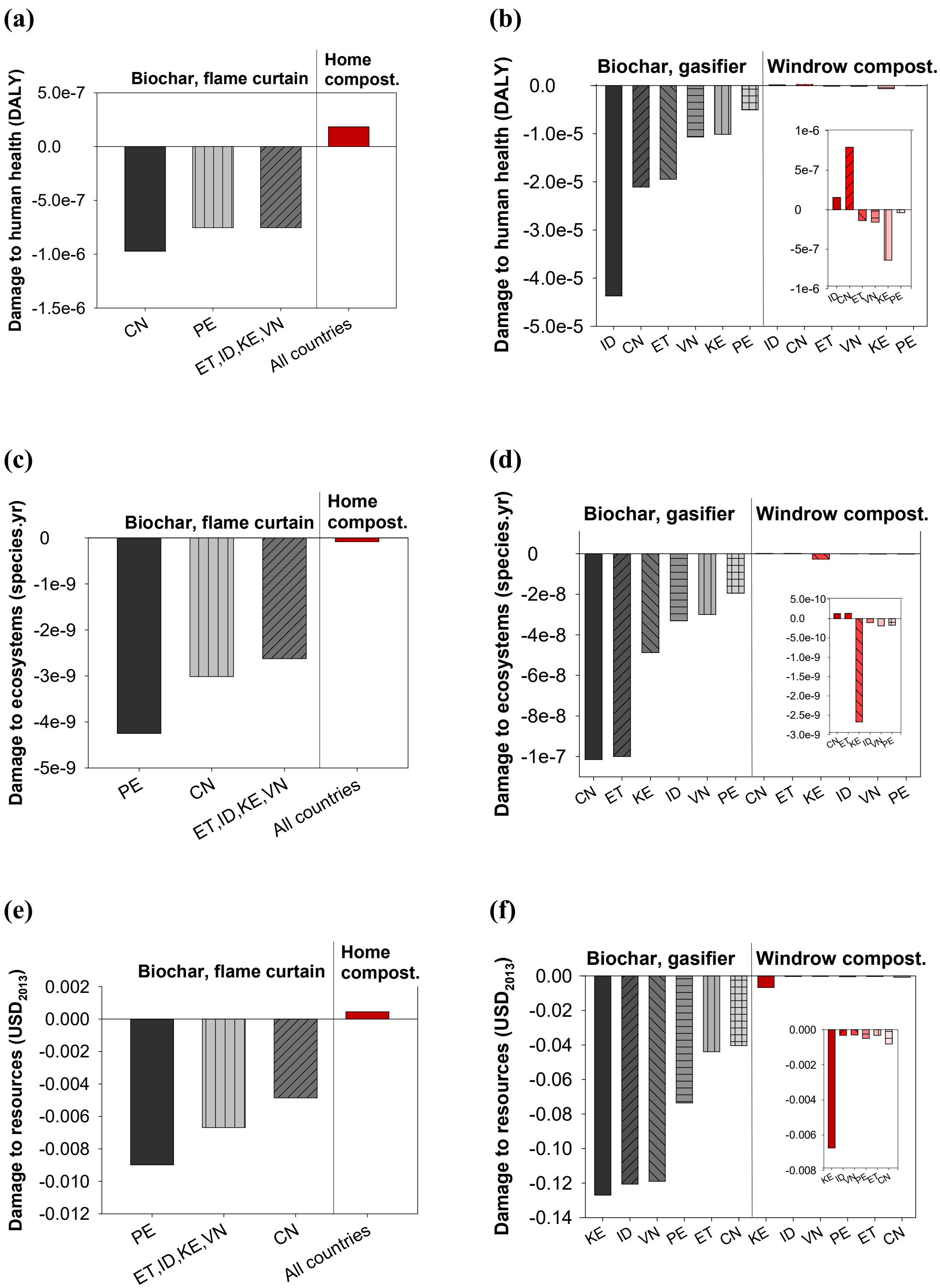
3.3. Pyrolysis systems perform better than composting

Irrespective of the country and type of biochar production method, biowaste management systems based on pyrolysis always performed significantly better when compared with their composting alternatives (see SI, Section S4 for statistical comparison between scenarios). For the composting scenarios, environmental benefits stemmed from avoided production of NPK fertilizers, but they were significantly smaller when compared to the benefits stemming from biochar used in agriculture. Indeed, if impact offsets were not considered in the biochar systems, environmental impact scores in biochar and composting scenarios would be statistically the same (results not shown). Previous studies of LCA applied to composting systems using midpoint indicators showed that composting itself carried environmental burdens (e.g. Martínez-Blanco et al. 2010; Boldrin et al. 2011), which can be outweighed by the avoided burden of dumping organic waste for some impact categories (Quirós et al. 2014). In this work, the definition of the functional unit means that the avoided burden of dumping organic waste is not considered. However, in agreement with previous studies, tradeoffs between burdens and benefits due to fertilizer replacement were observed in this study. In addition, some Monte Carlo runs did result in a positive overall impact score when inventory uncertainties were considered (while the median of 1000 runs was negative). This highlights the need for careful parameterization of composting processes, as overall impact is sensitive to uncertain and highly variable emission inventories.

3.4. Environmental impacts vary between countries

The differences in damage scores between countries were statistically significant in most cases for the flame curtain kiln systems (where comparisons were made between China, Peru, and remaining countries grouped together) and in nearly all cases for the gasifier systems (where comparison was made across all six countries) (SI, Section S4). The significant differences are caused by differences in outputs from processes, which are country-specific and contribute most to total impacts. In the flame curtain kiln scenarios, these processes are maize production, as effects of biochar are smaller in China in comparison to other countries, and energy use for irrigation, which is an important process for both China and Peru.

Differences in environmental performance of power generation are apparent for the scenarios where biochar is produced using the gasifier, where electricity generated by the gasifier directly replaces electricity from the grid mix (see SI, Section S1 for details). Damages from power generation are the largest (per kWh output) in Ethiopia (89% contribution of hydropower to total mix) and Indonesia (mainly due to the use of fossil-based energy sources like lignite and oil, altogether constituting 70% of Indonesian electricity grid mix) and were the lowest in Peru and Vietnam (both with relatively balanced mixes). The high impact in Ethiopia was unexpected, since the energy mix is largely renewable, but mainly originates from the relatively large ecosystem impacts associated with the use of water in hydropower plants. The Chinese electricity grid is comparable to those in Peru and Vietnam (per 1 kWh output), and the consistently smaller damage scores for China are explained by smaller yield increases due to biochar addition (14% increase), when compared to the increase expected in the five other countries (25%). This assumption is substantiated by the findings from Jeffery et al. (2011; 2017) who documented that the largest yield increases occur in tropical regions. Differences in windrow composting between countries are also determined by differences in the grid mix, as electricity is used for compost maintenance in windrow composting systems.



(a)
Biochar, flame curtain
Home compost.
Damage to human health (DALY)
5.0e-7
0.0
-5.0e-7
-1.0e-6
-1.5e-6
CN
PE
ET,ID,KE,VN
All countries
(b)
Biochar, gasifier
Windrow compost.
Damage to human health (DALY)
0.0
-1.0e-5
-2.0e-5
-3.0e-5
-4.0e-5
-5.0e-5
1e-6
5e-7
0
-5e-7
-1e-6
ID
CN
ET
VN
KE
PE
(c)
Biochar, flame curtain
Home compost.
Damage to ecosystems (species.yr)
0
-1e-9
-2e-9
-3e-9
-4e-9
-5e-9
PE
CN
ET,ID,KE,VN
All countries
(d)
Biochar, gasifier
Windrow compost.
Damage to ecosystems (species.yr)
0
-2e-8
-4e-8
-6e-8
-8e-8
-1e-7
5.0e-10
0.0
-5.0e-10
-1.0e-9
-1.5e-9
-2.0e-9
-2.5e-9
-3.0e-9
CN
ET
KE
ID
VN
PE
(e)
Biochar, flame curtain
Home compost.
Damage to resources (USD_{2013})
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
PE
ET,ID,KE,VN
CN
All countries
(f)
Biochar, gasifier
Windrow compost.
Damage to resources (USD_{2013})
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
0.000
-0.002
-0.004
-0.006
-0.008
KE
ID
VN
PE
ET
CN

Fig. 2. Damage to human health (panels a and b), ecosystems (panels c and d) and resources (panels e and f) per functional unit (management of 1 kg of wet biowaste in developing and middle-income countries) for different waste management systems: 1) flame curtain kiln with biochar use in agriculture compared to home composting with fertilizer replacement, and 2) gasifier with biochar use in agriculture and energy recovery compared to windrow composting with fertilizer replacement.

3.5 Economic impacts are mainly dependent on labor cost

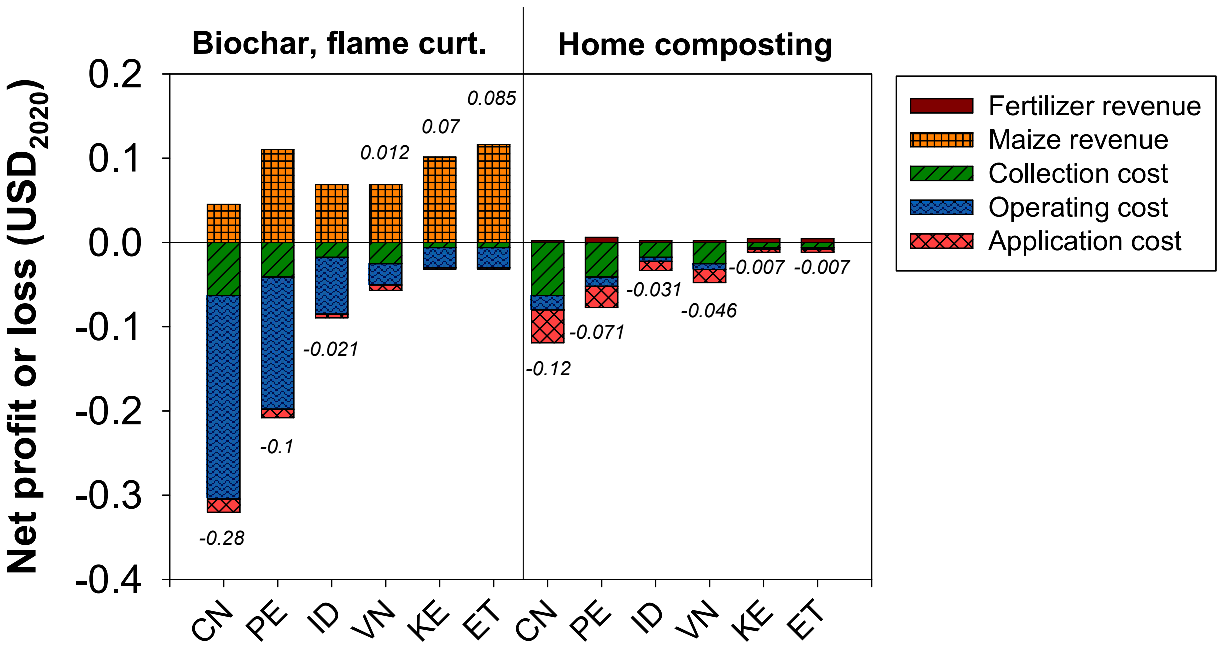
Panel A of Figure 3 presents results of the flame curtain kiln with the home composting system, and panel B presents results of the gasifier compared to the windrow composting system. The net value (profit) of R, as defined in equation (1) in USD per kg waste for each country is indicated above the top bars. Results show that neither home nor windrow composting are profitable for the individual decision maker in any of the six countries. The net loss is the biggest for China and Peru which have the highest labor costs. The value of offsetting fertilizer is small (below 0.01 USD per kg biowaste), and outweighed by the costs of composting, and this effect is more pronounced for windrow composting, which has higher capital and operating (labour) costs related to processing the waste. Thus, if there were no available alternatives, the economic assessment implies that the individual decision maker should leave the biowaste to decay in both rural and urban areas and instead use commercially produced mineral fertilizers, even though windrow composting in itself led to a positive environmental impact (Fig. 1d,1f).

The comparison of gasifier and flame curtain kiln systems yields more heterogeneous results across processes and countries. Using the biowaste for biochar production in the flame curtain pyrolysis system in rural areas was observed to be only profitable for Ethiopia, Kenya and Vietnam (panel A in Figure 3).

The two African countries have relatively high profitability since their low labor costs are outweighed by the value of the increase in maize production. This result is confirmed by other studies from Southern Africa, e.g. Dickinson et al. (2015), which reported positive net present value of biochar application. In Vietnam, making biochar with flame curtain kilns and applying it in maize cropping was observed to be only marginally profitable, while Indonesia was marginally unprofitable. These Asian countries have labor costs and per capita GDP levels which result in the value of maize almost equalizing costs. Under such conditions, studies show that using residues for biochar is not consistently profitable (e.g review by Majumder et al. 2019). It is clear that labor costs are especially important in the determination of whether it is profitable to opt for a low resource, but labour intensive method of producing biochar such as flame curtain kilns. Indeed, high-technological production of biochar in large kilns is a more normal method of production of biochar in China (Braby 2019; Clare et al., 2014; Pan et al., 2015). A recent review of biochar cost constraints confirms that high-value crops in tropical locations with low income and biochar-focused small-scale production were overall significant predictors of biochar scenario financial feasibility (Robb et al. 2020).

Using the gasifier pyrolysis system is not profitable in any country, and the least profitable in China (net loss of -1.58 USD) and Peru (net loss of -0.93 USD). These results stem from the fact that the value of the avoided electricity and maize production is outweighed by high capital investment and operating costs. The African countries are the closest to profitable (net losses around 0.30 USD) as maize and electricity prices vary less between countries than labor costs, and it follows therefore that revenues are weighted higher in the calculation for the countries that have low labor costs and GDP/capita. These results are in line with the assumptions made regarding gasifier capacity and annual biochar production, which is an important factor when calculating the annualized investment costs. The annual biochar production would have to more than double for the African countries to obtain a net profit out of the gasifier investment per kg waste. The operating costs used in calculations are also important and the average GDP-scaled figures used may mask geographical variations and costs that in reality could be lower in some areas due to e.g. underemployment and informal labour markets. Despite this, operating costs would need to be reduced substantially to make the gasifier investment worthwhile for all six countries.

(a)


Biochar, flame curt.
Home composting
Net profit or loss (USD2020)
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0.085
0.07
0.012
-0.021
-0.1
-0.28
-0.007
-0.007
-0.031
-0.046
-0.071
-0.12
CN
PE
ID
VN
KE
ET
CN
PE
ID
VN
KE
ET
Fertilizer revenue
Maize revenue
Collection cost
Operating cost
Application cost

(b)

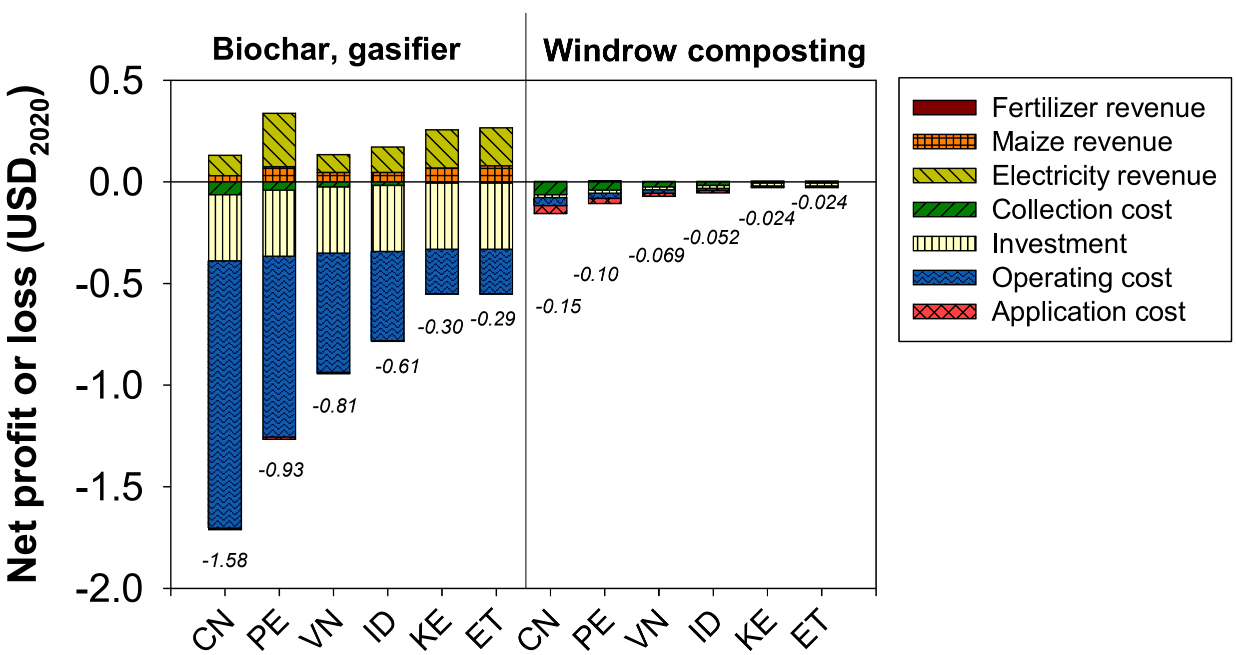

Biochar, gasifier
Windrow composting
Net profit or loss (USD2020)
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-0.30
-0.29
-0.61
-0.81
-0.93
-1.58
-0.024
-0.024
-0.052
-0.069
-0.10
-0.15
CN
PE
VN
ID
KE
ET
CN
PE
VN
ID
KE
ET
Fertilizer revenue
Maize revenue
Electricity revenue
Collection cost
Investment
Operating cost
Application cost

Fig. 3. Main components of annual costs (negative bars) and revenues (positive bars) and net profit or loss in USD/kg waste (i.e., management of 1 kg of wet biowaste in developing and middle-income countries) for different waste management systems: 1) flame curtain kiln with biochar use in agriculture compared to home composting with fertilizer replacement, and 2) gasifier with biochar use in agriculture and energy recovery compared to windrow composting with fertilizer replacement. Countries are ranked according to increasing net value in the pyrolysis systems, separately for (a) and (b) panels.

3.6 A comparison between environmental and economic impacts is needed to arrive at the best decision

Comparing the environmental and economic results presents an interesting story. Biochar production was demonstrated to be preferable compared to composting applications in all cases from an environmental perspective. However, a win-win situation for the environment and the economy (net market profits) was only observed in rural areas of Ethiopia, Kenya and Vietnam, when the flame curtain kiln was used. For the other flame curtain scenarios for making biochar in rural areas of China, Indonesia and Peru, there is a trade-off between positive environmental impacts for society and net market loss for the individual decision-maker (firm or individual farmer). While the economic results for the flame curtain kiln are relatively close to profitability in Indonesia and Peru, the net economic loss for the use of the gasifier in urban areas is substantially higher per kg waste in all countries. Hence, there are clear trade-offs between environmental and economic impacts. The factors that play the largest role in decision making are the relatively high investment costs for the gasifier, operating and labor costs and alternative sources of income.

3.7 Limitations

This study provides valuable insights in to impacts of biochar production and agricultural use, there are limitations. This study focused on six countries and used data from one specific area per country. Results may be used indicatively for other rural and urban areas with similar characteristics but cannot be directly applied to them. In addition, the systems studied are limited to a small number of factors that influence environmental and economic performance. Impacts of biochar on a variety of sustainable aspects such as poverty reduction, affordability of clean energy investments, and related topics are outside the scope of the paper but should be included in more comprehensive evaluations addressed in further research aiming towards e.g. strengthening policy support for more widespread adoption of biochar use (Pourhashem et al. 2018). It also important to notice that all economic calculations assume connections to existing national electricity grid systems. For situations where gasifiers substitute local fossil fuel generated electricity, or when capacity problems in net systems may be of concern, the electricity produced by gasifiers may became more profitable.

4. Conclusions

This work investigated the feasibility of producing and using biochar for agricultural purposes. Through a systematic review of various scenarios addressing life cycle environmental impacts and economic aspects for countries with various geographical and socio-economic conditions, it clear that the feasibility of introducing biochar in rural and middle-income countries varies. While all cases resulted in environmental benefits of biochar production and use, clear differences between countries were observed when economic impacts were added to the scenarios.

The better performance of biochar when compared to composting was documented, but positive net economic benefit was only achieved for developing countries with low labor cost (Ethiopia, Kenya and Vietnam) when using simple production methods. The use of the gasifier was very costly and did not yield any positive economic impacts (profits) under any of the modelled scenarios. Adding the net effect of electricity revenue from gasifier use does not compensate for the higher investment and operating cost of gasifiers. This study has clearly highlighted that both environmental and economic impacts must be considered in order that decision makers (companies or farmers) can arrive at the most appropriate strategy.

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