Low tech biochar production could be a highly effective nature-based solution for climate change mitigation in the developing world

Camila Aquije · Hans-Peter Schmidt · Kathleen Draper · Stephen Joseph · Brenton Ladd

Received: 14 May 2021 / Accepted: 15 September 2021 / Published online: 29 September 2021
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2021

Abstract

Aim To compare the climate change mitigation benefits of nature-based solutions for management of municipal green waste with conventional management.

Methods This study analyzed the carbon footprint of managing one ton of municipal green waste (MGW) in Lima Peru under 4 different scenarios: 1) Final disposal in authorized landfill, 2) Final disposal in informal landfill, 3) composting and 4) biochar production using a low-cost, low tech Kon-Tiki reactor.

Results The results demonstrate the very clear potential for climate change mitigation from biochar production using low tech and therefore accessible technology in a typical developing world context. The carbon footprint of producing biochar was lower than for composting and biochar and compost both had carbon footprints significantly lower than landfilling.

Conclusion We argue that the standards used by nascent platforms for trading carbon removal credits generated by biochar should relax the technology requirement to favor engagement and participation of small-scale market participants in low-income countries. Waste management in the developing world presents significant challenges but often starts from a very low base which means there is large potential for reducing emissions, as well as for sequestering carbon.

Keywords Biochar · Compost · Landfill · Municipal green waste · Climate change mitigation · Carbon footprint

Introduction

There has been significant progress in research towards developing biochar formulations that are optimised for specific purposes, such as heavy metal immobilization, carbon sequestration, agronomy, as an additive for animal feed etc. (Bolan et al. 2021). At the same time there is growing awareness among
scientists and decision makers that simply curtail-
ing greenhouse gas (GHG) emissions will be insuf-
ficient to avert a climate crisis (Ravi et al. 2016; Li
et al. 2019; Rogelj et al. 2021). The amount of carbon
in the earth’s atmosphere has reached a level were
investment in strategies and technologies that gener-
ate negative emissions, i.e., that draw down the level
of carbon dioxide in the atmosphere, have become
necessary (Alcalde et al. 2018; Mullingan et al. 2020;
Carton et al. 2020; EBIC 2021). The possibilities for
doing this are limited (Fuss et al. 2014; IPCC 2018).

Nevertheless, it is clear that biochar production
and use is one such ready to implement technology
/ land management strategy that could generate sig-
ificant amounts of negative emissions (Smith 2016).
For this reason, we are now seeing the development
of trading platforms for the buying and selling of car-
bon removal credits related to biochar production,
I.e., Puro (2021) and Carbonfuture (2021).

Whilst such positive developments are to be wel-
comed, there is need for refinement of the general
approach so that it is more inclusive and doesn’t
exclude, by design, participation from actors in the
developing world. The above-mentioned trading
platforms and standards tend to place an emphasis
on using state-of-the-art technology for biochar pro-
duction to minimize emissions during carbonization.
This is perfectly reasonable and doable in a developed
world context, were effective and advanced waste
management systems and legislation are already in
place. In the developing world, waste management
often starts from a much lower base and a requirement
for heavy upfront investment is likely to act as a bar-
rrier to investment and participation simply because
the economic environment is higher risk in the devel-
oping world. Further, organic waste (or “biological”
to differentiate from the label “organic”) is often
highly heterogenous. At points of aggregation for
crops like coffee and cacao, volumes of waste may be
small and seasonal. In these contexts, the requirement
for significant upfront investment in state-of-the-art
technology may act as a barrier to participation, even
though significant emission reductions are possible
without the aid of state-of-the-art technology.

The criteria for whether a project achieves nega-
tive emissions and whether it is eligible for carbon
removal finance should ideally be anchored in some-
thing like the concept of additionality developed
by the UN for REDD. In Perú in 2014 a total of
7.5 million metric tons of urban solid waste (which
includes organics, construction waste, medical waste
etc.) was generated; it is estimated that 47% of this
waste ended up in informal (illegal) landfills and
only 21% ended up in licenced landfills (Ziegler et al.
2018). If we focus exclusively on municipal green
waste, the waste biomass obtained through the regu-
lar maintenance of urban green space, the figures are
still large. For example, in Lima a mega city on the
Peruvian coast, we see the generation of 1,382 tonnes
of municipal green waste per month (SIGERSOL
2021). Only a small fraction of this is composted and
the majority is destined for either formal or infor-
mal landfills were the green waste decomposes in
an anoxic environment, liberating potent greenhouse
gases such as methane and nitrous oxide (Eklund
et al. 1998). In this context the production of biochar
from municipal green waste in an artisanal biochar
reactor such as a Kon-tiki kiln (Ithaka 2021) could be
considered a significant improvement over the status
quo. Here we calculate the carbon footprint of munic-
ipal green waste management using four different
strategies: 1) final disposition in a licenced landfill, 2)
final disposition in an informal landfill, 3) compost-
ing, and 4) biochar production using low cost, artisa-
nal technology.

Materials and methods

Using one ton of Municipal Green Waste (MGW) as
the unit of analysis we calculated the carbon footprint
of managing municipal green waste in Lima, Peru
under four different scenarios: 1) business as usual
(licensed landfill), 2) business as usual (unlicensed
landfill), 3) composting and 4) biochar production via
a Kon-Tiki. In all four cases we assume that the car-
bon content of plant biomass is 50%, following IPCC
(2014).

In all four scenarios the first significant emis-
ion of GHG comes from transportation of biomass.
Lima is a megacity and transport distances vary
depending on proximity to the urban core. Never-
theless, transport associated emissions are inevita-
able because landfill sites are located on the outskirts
of the city, just beyond city limits, where the impact
of waste management on residents is reduced. The
informal landfills are even further from the urban
core. Using the specific example of MGW from the
municipality of Lurin on Lima’s southern fringe we assume the emission of 340 g of CO₂eq emitted per ton of municipal green waste per km in a medium sized truck (Seo et al. 2016). In this specific case changing from landfilling to either composting or biochar production reduces transport emissions (Table 1) because the biochar /compost operation is closer to the urban core than the landfill sites (Appendix s1).

The step after transporting is the processing of the waste. In the first and seconds scenarios, in which MGW is disposed of in formal and informal landfills there are many uncertainties around the amount of GHG released from the relevant biomass. Nevertheless, values are likely high since the anoxic conditions found in landfill favor the liberation of gases such as methane and nitrous oxide (Eklund et al. 1998). The emission of GHGs (carbon dioxide, methane and other trace gases and particulates (CO, NOx, PM₂.₅, PM₁₀) in percentage terms and the corresponding multipliers for converting these to CO₂ equivalents are from Babu et al. (2014), which were then applied to the baseline of 1 ton of MGW.

In the third scenario, in which the MGW is composted, we assume that 52% of the C contained in the waste biomass is retained in the compost, after Tiquia et al. (2002). For the remaining 48% C we assume 3% is lost as methane and 45% is liberated as CO₂, based on Boldrin et al. (2009). Estimates of CO₂eq from particulates and traces gases during composting are based on Van Haaren et al. (2010). For the production of compost, we also calculate the emissions that result from pumping the ground water needed for the composting process. Ideally compost should be 60% water by weight. We assume composting takes place over 60 days (after Zhu-Barker et al. 2016) although it is important to note that the actual time required for composting can be significantly shorter or longer depending on feedstock and management practices (Kuhlman 1990; Pace et al. 1995).

Emissions are not the only consideration with organics management, water usage is also critical especially in areas prone to drought. In Lima the rate of evaporation is 952.9 mm per annum (MIDAGRI

| Table 1 Calculation of carbon footprint using 4 different strategies for management of municipal green waste. A multiplier of 25 was used to convert methane into CO₂eq |
|---------------------------------|-----------------|------------------|------------------|
| Licensed Landfill               | Informal Landfill | Compost (Windrow) | Biochar (Kon-Tiki) |
|---------------------------------|-----------------|------------------|------------------|
| green waste (kg)                | 1000            | 1000             | 1000             | 1000             |
| Kg of C in 1000 kg green waste  | 500             | 500              | 500              | 500              |
| biomass transport emissions (kg of C) | 2.47   | 2.47             | 0.83             | 0.83             |
| kg of C embodied in compost or biochar after processing | -             | -                | 240              | 150              |
| kg of C liberated as GHG during composting or biochar production | -             | -                | 260              | 350              |
| kg of C liberated as GHG when pumping ground water for composting | -             | -                | 0.13             | -                |
| kg of C liberated as GHG when pumping ground water for quenching biochar | -             | -                | -                | 0.307            |
| C emissions from packaging/bags | -               | -                | 6.37             | 3.822            |
| kg of C liberated as GHG to fabricate the metal needed to build a Kon-Tiki oven | -             | -                | -                | 0.37             |
| CO₂ emissions from waste treatment strategy (kgs of C) | 86.88           | 72.43            | 243.75           | 334.53           |
| CH₄ emissions from waste treatment strategy (CO₂eq)          | 1398.54         | 1748.18          | 406.25           | 51.82            |
| CO₂eq of trace gases and particulates (PM25, PM10, CO, NOx, Volatile Organics, Hydrocarbons) | 3.87          | 3.87             | 2.028            | 83.77            |
| Transport emissions (CO₂eq) for moving compost or biochar to its final destination | -               | -                | 0.83             | 71.5             |
| TOTAL (kg CO₂eq.)               | 1492            | 1827             | 660.45           | 546.27           |

 Springer
Thus, an area of 2m², i.e., the area that 1000 kg of MGW would occupy, would require 317.6 L of water for optimal composting. In Lurin ground water is used and obtained using a 1 horsepower pump. This in turn requires 32.9 W of electricity which results in 0.013 kg of CO₂eq. These calculations are based on data from the U.S Energy Information Administration (EIA 2020) who report that 0.42 kg of CO₂eq are emitted per kWh. We assume the compost produced from a ton of MGW gets packaged in 10 laminated plastic bags (Table 1) that have an emission of factor of 0.637 kgCO₂eq/bag (Ma et al. 2019). Finally, once produced compost needs transportation to its place of use. We assume that any compost produced will be returned to the urban green spaces from which the waste biomass was collected. If we again assume emissions of 340 g of CO₂eq emitted per ton, per km, for material transported in a medium sized truck (Seo et al. 2016), we arrive at a figure of 0.3 kg of CO₂eq of additional transport emissions linked to managing one ton of MGW via composting.

Finally, for the scenario in which MGW is used to produce biochar we assume that 30% of the C contained in the feedstock biomass is retained in the biochar produced, after Mohammadi et al. (2016). For the 70% of the C content of the feedstock which is lost during biochar production, we assume that 95.6% is liberated to the atmosphere in the form of CO₂, 0.5% in the form of methane and 3.9% as other gases (CO, Volatile organic compounds, NOx, and particulates), based on the measurements of Cornelissen et al. (2016). Emission factors for converting methane and the other trace gases into CO₂eqs are from Babu et al. (2014). We also calculated the emissions embodied in metal used to manufacture a Kontiki oven. For every ton of steel produced we assume that 1.85 tons of CO₂eq are emitted to the atmosphere (Hoffmann et al. 2020). A Kon-Tiki kiln uses 200 kg of metal thus resulting in the emission 370 kg CO₂eq. Every kiln has a life cycle of roughly 300 burns. Each individual burn consumes roughly a ton of MGW and produces around 320 kg of biochar. The 370 kg CO₂eq embodied in the steel used to fabricate a Kontiki thus needs to be amortized across the biochar produced during the lifetime of the kiln. The result is a minor level of emissions from the metal embodied in the oven (Table 1). To quench 320 kg of biochar produced in a Kon-Tiki we assume requires 378.54 L of water (after McAvoy and Dettenmaier 2019).

We assume the biochar produced with a ton of MGW is packaged in 6 laminated plastic bags that have an emission of factor of 0.637 kgCO₂eq/bag (Ma et al. 2019). Once produced the biochar needs to be transported to its final destination. In Peru the most likely final destination is San Martin, Peru’s most important Cacao growing region. In San Martin biochar is being used to remediate soils with high levels of cadmium, in response to Regulation (EC) No 1881/2006 of the European Union which prohibits the import of cacao that contains more than 0.8 ppm of cadmium. The distance from Lima to San Martin is 630 km. We again assume 340 g of CO₂eq emitted per ton of material, per km, in a medium sized truck (Seo et al. 2016). We assume a medium sized truck because the medium sized trucks that bring agricultural product to Lima generally return less than full and could be used to transport biochar. In this scenario the biochar produced from one ton of MGW would result in an additional 71.5 kg of CO₂eq of transport related emissions per ton of MGW processed.

Results and discussion

The analysis of the carbon footprint across the 4 alternative strategies for managing MGW suggests that biochar should be the preferred treatment method from a carbon accounting perspective, followed by composting, followed by final disposition in licensed or unlicensed landfills (Table 1). If we extend the carbon footprint analysis to consider the fate of the carbon contained in the compost and biochar produced in scenarios 3 and 4 a slightly different picture emerges. The half-life of compost can be as low as 45 days (Araújo et al. 2020). Biochar on the other hand may persist in soil over millennial time scales (Spokas 2010), and may even promote the accumulation of new non-pyrogenic soil carbon (Weng et al. 2017). Thus, if we assume a half-life of compost equivalent to the figure reported in Araújo et al. 2020, then an additional 130 kg of CO₂eq will be liberated to the atmosphere from compost after the said 45 days have elapsed. The half-life for biochar is measured in decades to millennia with minimal loss of carbon to the atmosphere. Thus, the carbon footprint of biochar is likely significantly improved relative to compost. However, in a real-world context both composting
and biochar production should be considered synergistic for management of MGW. MGW is heterogeneous containing components that are easy to compost (e.g., lawn clipping, leaves) and complicated to pyrolyze, and a woody component that is difficult to compost but relatively easy to pyrolyze (Fig. 1).

Governance over waste management practices in developing nations such as Peru is far from optimal. If heavy investment in state-of-the-art pyrolysis or gasification technology is required before biochar production becomes eligible for carbon credits, then very likely it will remain business as usual with the continuation of high rates of GHG emission from poorly managed landfills. We think the nascent standards for carbon removals from biochar should be expanded to include low-polluting, low-cost technologies to enable participation by actors in developing world contexts. The calculations in Table 1 demonstrate that every ton of MGW diverted from landfill to artisanal biochar production decreases CO₂eq emissions to the atmosphere by one ton. Extrapolating to the amount of MGW produced each month in Lima, we arrive at a figure of 1300 tons CO₂eq emissions mitigated per month. If we then consider waste management in all the other megacities in the developing world where waste management likely starts from the same low base the potential for climate change mitigation begins to look promising.

The development of the nascent trading platforms for negative emissions generated by biochar are a welcome development. We also agree that implementing state of the art technology is a laudable goal that would allow maximum control of production parameters such as temperature. This in turn would allow the optimization of biochar for specific purposes (Ippolito et al. 2020). However, given the significant emissions reductions of low-tech carbonization of MGW over current practices outlined in this analysis, we argue that low tech carbonization of organics should be financially incentivized to rapidly motivate waste management operators in the developing world to adopt carbonization as the preferred management strategy. Leveraging the emerging carbon removal markets could be an effective pathway to providing the needed financial incentives.

Acknowledgements The authors would like to thank the following people who contributed to the article by commenting on the first drafts:

Funding Seed funding from the research office at the Universidad Cientifica del Sur (grant 027-2021-PRO99) is gratefully acknowledged.

Declarations

Conflict of interest The authors declare no conflicts of interest.
Nature 591: 365–368. https://www.nature.com/articles/d41586-021-00662-3.

Seo J, Park J, Oh Y, Park S (2016) Estimation of total transport CO₂ emissions generated by medium-and heavy-duty vehicles (MHDVs) in a sector of Korea. Energies 9(8):638. https://doi.org/10.3390/en9080638

SIGERSOL (2021) Sistema de Información para la Gestión de Residuos Sólidos. Ministerio del Ambiente https://sistemas.minam.gob.pe/SigersolMunicipal/#/panel. Accessed 6 July 2021

Smith P (2016) Soil carbon sequestration and biochar as negative emission technologies. Glob Change Biol 22(3):1315–1324. https://doi.org/10.1111/gcb.13178

Spokas KA (2010) Review of the stability of biochar in soils: predictability of O: C molar ratios. Carbon Management 1(2):289–303. https://doi.org/10.4155/cmt.10.32

Tiquia SM, Richard TL, Honeyman MS (2002) Carbon, nutrient, and mass loss during composting. Nutr Cycl Agroecosyst 62(1):15–24. https://doi.org/10.1023/A:1015137922816

Van Haaren R, Themelis NJ, Barlaz M (2010) LCA comparison of windrow composting of yard wastes with use as alternative daily cover (ADC). Waste Manage 30(12):2649–2656. https://doi.org/10.1016/j.wasman.2010.06.007

Weng ZH, Van Zwieten L, Singh BP, Tavakkoli E, Joseph S, Macdonald LM, Rose TJ, Rose MT, Kimber SW, Morris S, Cozzolino D (2017) Biochar built soil carbon over a decade by stabilizing rhizodeposits. Nat Clim Chang 7(5):371–376. https://doi.org/10.1038/nclimate3276

Zhu-Barker X, Bailey SK, Burger M, Horwath WR (2016) Greenhouse gas emissions from green waste composting windrow. Waste Manage 59:70–79. https://doi.org/10.1016/j.wasman.2016.10.004

Ziegler K, Margallo M, Aldaco R, Irabien J, Vázquez I, Kahhat R (2018) Environmental performance of peruvian waste management systems under a life cycle approach. Chem Eng Trans 70:1753–1758. https://doi.org/10.3303/CET1870293

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.