



FACULTAD DE CIENCIAS AMBIENTALES
CARRERA PROFESIONAL DE INGENIERÍA AMBIENTAL

**“EVALUACIÓN DEL CICLO DE VIDA DEL MANEJO DE
RESIDUOS VERDES MUNICIPALES MEDIANTE LA GESTIÓN DE
RELLENOS SANITARIOS, COMPOST Y BIOCARBÓN (KON-TIKI)
EN LIMA”**

Tesis para optar el título profesional de:

INGENIERA AMBIENTAL

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Presentada por la/el estudiante/bachiller:

- **Camila Alessandra Aquije Ramos**

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Asesorado por: Dr. Brenton Mark Ladd

Luego de haber evaluado el informe final de tesis y evaluado el desempeño del estudiante de la carrera de Ingeniería Ambiental a en la sustentación, concluyen de manera unánime (x) por mayoría simple () calificar a:

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DEDICATORIA

A mi familia, especialmente a mi mamá, Inés Ramos, quien siempre me apoyó durante todo el proceso de mi carrera.

A la memoria de mi papá, Arturo Aquije, quien me apoyó y me enseñó a nunca rendirme e ir siempre hacia adelante.

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RESUMEN

Objetivo Comparar los beneficios de la mitigación del cambio climático con soluciones basadas en la naturaleza para la gestión de residuos verdes municipales convencionales.

Métodos Este estudio analizó la huella de carbono del manejo de una tonelada de residuos verdes municipales (RVM) en Lima Perú bajo 4 escenarios diferentes: 1) Disposición final en relleno sanitario autorizado, 2) Disposición final en un vertedero, 3) compostaje y 4) producción de biocarbón, utilizando un reactor Kon-Tiki de bajo costo y tecnología.

Resultados Los resultados demuestran el potencial muy claro para la mitigación del cambio climático a partir de la producción de biocarbón utilizando tecnología de baja tecnología y, por lo tanto, accesible en un contexto típico del mundo en desarrollo. La huella de carbono de la producción de biocarbón fue más baja que la del compostaje y el biocarbón y el compost tuvieron huellas de carbono significativamente más bajas que en los rellenos sanitarios y vertederos.

Conclusión Argumentamos que los estándares utilizados por las plataformas nacientes para comercializar los créditos de eliminación de carbono generados por el biocarbón deberían ablandar el requisito de tecnología para favorecer el compromiso y la participación de los participantes del mercado a pequeña escala en los países de bajos ingresos. La gestión de residuos en el mundo en desarrollo presenta desafíos importantes, pero a menudo comienza desde una base muy baja, lo que significa que existe un gran potencial para reducir las emisiones, así como para secuestrar carbono.

Palabras clave: Biocarbón, Compost, Vertedero, Residuos verdes municipales, Mitigación del cambio climático, Huella de carbono.

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 cred-its generated by biochar should relax the technology requirement to favor engagement and participation of small-scale market participants in low-income coun-tries. 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.

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	<p>participants in the so-called developing world. Waste management in developing world contexts often starts from a very low base which means there is very large potential for both reducing emissions as well as sequestering carbon.</p>
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Low tech biochar production could be a highly effective nature-based solution for climate change mitigation in the developing world.

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Abstract

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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 curtailing greenhouse gas (GHG) emissions will be insufficient 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 where investment in strategies and technologies that generate negative emissions, i.e., that draw down the level of carbon dioxide in the atmosphere, have become necessary (Alcalde et al. 2018; Mulligan 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 significant amounts of negative

emissions (Smith, 2016). For this reason, we are now seeing the development of trading platforms for the buying and selling of carbon removal credits related to biochar production, i.e., Puro (2021) and Carbonfuture (2021).

Whilst such positive developments are to be welcomed, 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 production to minimize emissions during carbonization. This is perfectly reasonable and doable in a developed world context, where 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 barrier to investment and participation simply because the economic environment is higher risk in the developing world. Further, organic waste (or "biological" to differentiate from the label "organic") is often highly heterogeneous. 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 negative emissions and whether it is eligible for carbon removal finance should ideally be anchored in something 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 regular 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 informal landfills where 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 (Ithika 2021) could be considered a significant improvement over the status quo. Here we calculate the carbon footprint of municipal green waste management using four different strategies: 1) final disposition in a licenced landfill, 2) final disposition in an informal landfill, 3) composting, and 4) biochar production using low cost, artisanal 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 carbon content of plant biomass is 50%, following IPCC (2014).

In all four scenarios the first significant emission of GHG comes from transportation of biomass. Lima is a megacity and transport distances vary depending on proximity to the urban core. Nevertheless, transport associated emissions are inevitable 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 second 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, NO_x, PM_{2.5}, 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 trace 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-Baker et al. 2017) 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 (Kuhlmann, 1990 and 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, n.d.). Thus, an area of 2m², i.e., the area that 1000 kg of MGW would occupy, would require 317.6 liters 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 0.13 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, NO_x, 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 200kg of metal thus resulting in the emission 0,370 kg CO₂eq. Every kiln has a life cycle of roughly 300 burns. Each individual burn consumes roughly a ton of MGW and produces around 320kg of biochar. The 0,37 kg CO₂eq embodied in the steel used to fabricate a Kon-tiki 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 liters of water (after McAvoy & Detternmaier, 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 0.8ppm of cadmium. The distance from Lima to san Martin is 630km. 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-pyrolytic soil carbon (Weng et al. 2017). Thus, if we assume a half-life of compost equivalent to the figure reported in Araujo 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 (Figure 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.

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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
CO ₂ emissions from waste treatment strategy (kgs of C)	86.88	72.43	243.75	334.53
CH ₄ emissions from waste treatment strategy (CO ₂ eq)	1398.54	1748.18	406.25	51.82
CO ₂ eq of trace gases and particulates (PM ₂₅ , PM ₁₀ , CO, NO _x , Volatile Organics, Hydrocarbons)	3.87	3.87	2.028	83.77
Transport emissions (CO ₂ eq) for moving compost or biochar to its final destination.	-	-	0.83	71.5
TOTAL (kg CO₂eq.)	1492	1827	660.45	546.27



Figure 1. Municipal green waste is a heterogenous mixture that includes components (cut grass) for which composting is an ideal waste management strategy. There is also a woody component obtained via pruning trees and shrubs that would require additional processing (chipping) before composting becomes a viable strategy. The woody component is also likely to contain a high lignin content which will increase the time, cost and emissions of composting.

VERSIÓN INICIAL ENVIADA A PUBLICAR**Low tech biochar production could be a highly effective nature-based solution for climate change mitigation in the developing world.**

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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 waste management achieved via landfilling.

Conclusion: We argue that the standards used by nascent platforms for trading carbon removal credits generated by biochar should be expanded to include small scale market participants in the so-called developing world. Waste management in the developing world presents significant challenges but often starts from a very low base which means there is very large potential for reducing emissions as well as sequestering carbon.

Keywords: biochar, compost, landfill, municipal green waste, climate change mitigation, carbon footprint.

Introduction

It is now clear that the production and use of biochar in agriculture and soil remediation has a clear economic value proposition (Thomas et al. 2020; Ladd et al. 2018). At the same time there is growing awareness among scientists and decision makers that simply curtailing greenhouse gas (GHG) emissions will be insufficient to avert a climate crisis (Ravi et al. 2016; Li et al. 2019; Rogelj et al. 2021). The level of carbon pollution in the earth's atmosphere has reached a level where humanity must increase investment in technologies and strategies that generate negative emissions, i.e., which actually draw down the level of carbon dioxide in the atmosphere (Alcalde et al. 2018; Mulligan et al. 2020; EBIC 2021). The possibilities for doing this are surprisingly limited (Schlesinger 2020). Nevertheless, it is clear that biochar production and use is one such ready to implement technology / land management strategy that could generate significant amounts of negative emissions. For this reason, we are now

seeing the development of trading platforms for the buying and selling of carbon credits for the negative emissions generated with biochar, i.e., Puro (2021) and Carbonfuture (2021).

Whilst such positive developments are to be welcomed, 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 production to minimize emissions during the process. This is perfectly reasonable and doable in a developed world context, where 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. Further, the generation of organic waste (or "biological" to differentiate from the label "organic") is highly heterogeneous. At points of aggregation for crops like coffee and cacao volumes of waste are 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.

The criteria for whether a project achieves negative emissions should ideally be anchored in something like the concept of additionality developed by the UN for REDD. For example, in Lima a mega city on the Peruvian coast, we see the generation of 2,500 tonnes of municipal green waste per month. Only a small fraction of this is composted. In Lima in 2014 a total of 7.5 million metric tons of urban solid waste was generated; 47% of the waste ended up in informal (illegal) landfills and only 21% was sent to licensed landfills (Ziegler et al. 2018). For both formal and informal landfills 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 (Ithika 2021) could be considered a significant improvement

over the status quo. Here we calculate the carbon footprint of municipal green waste management using four different strategies: 1) final disposition in a licenced landfill, 2) final disposition in an informal landfill, 3) composting, and 4) biochar production using low cost, artisanal 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 (final disposition in licensed landfills), 2) business as usual (final disposition in unlicensed landfills), 3) the production of compost and 4) the production of biochar using a Kon-Tiki reactor. In all four cases we assume that the plant biomass carbon content is 50% following IPCC (2014).

In all four scenarios the first significant emission of GHG comes from transportation of biomass. Lima is a megacity and transport distances vary depending on proximity to the urban core. Nevertheless, transport associated emissions are inevitable 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 CO₂ 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 plant 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 at landfill sites favor the liberation of potent GHGs such as methane and nitrous oxides (Eklund et al. 1998). For the specific case of landfill on the hyper arid Peruvian coast, we have an already a completed life cycle analysis applicable to both formal and informal landfills (Ziegler et al. 2019).

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). 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. In Lima the rate of evaporation of 952.9 mm per annum (MIDAGRI, n.d.). Thus, an area of 2m², i.e., the area that 1000 kg of MGW would occupy, would require 317.6 liters 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 CO₂ equivalent from the electricity used to pump water per ton of MGW composted.

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 the production process, we assume that 96% is liberated to the atmosphere in the form of CO₂, and .05% in the form of methane, based on the measurements of Cornelissen et al. (2016). Finally, we 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 CO₂ are emitted (Hoffmann et al. 2020). A

Kon-Tiki kiln uses 200kg of metal thus resulting in the emission 0.37 kg CO₂. Every kiln has a life cycle of roughly 300 burns and each individual burn produces around 320kg of biochar. The 0.37 kg CO₂ embodied in the steel used to fabricate a Kontiki oven was distributed across the biochar produced across the 300 burns just mentioned resulting in an insignificant level of emissions (Table 1).

Results

The analysis of the carbon footprint across the 4 alternative strategies for managing MGW suggests that biochar should be the preferred treatment method, followed by composting, followed by final disposition in licensed or unlicensed landfills (Table 1). If we extend the time frame of the carbon foot print analysis and consider the fate of the carbon contained in either compost or biochar once added to soil then 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 favour the accumulation of new non-pyrogenic soil carbon (Weng et al. 2017). Thus, if we extend the carbon footprint analysis to 45 days after the compost or biochar has been incorporated into soil then an additional 130 kg of CO₂e will be liberated to the atmosphere from compost. The corresponding figure for biochar is likely to be insignificant and the carbon footprint of biochar is thus likely significantly improved relative to compost. However, in a real-world context both composting and biochar production are synergistic for management of MGW. MGW is heterogenous. It contains certain components (lawn clipping, leaves) that are easy to compost and complicated to pyrolyze and a woody component that is difficult to compost but relatively easy to pyrolyze (Figure 1).

Discussion

Governance over waste management practices in developing nations such as Peru is far from optimal. If heavy investment in state-of-the-art 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 expand the technology requirement to favor 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 2500 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. However, the general framework needs to be more inclusive. Allowing lower cost production via artisanal technology could potentially facilitate participation from actors in the developing world and this in turn could promote a large amount of climate change mitigation.

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Kg of C liberated as GHG during composting or biochar production	-	-	260.00	350.00
Kg of C liberated as GHG when pumping ground water for composting	-	-	0.01	-
Kg of C liberated as GHG to fabricate the metal needed to build a Kon-Tiki oven	-	-	-	0.37
CO ₂ emissions from waste treatment strategy	-	-	243.75	334.53
CH ₄ emissions from waste treatment strategy (CO ₂ eq)	-	-	406.25	46.25
Subtotal emissions from waste treatment strategy	1359.00	1497	650	380.78
TOTAL (kg CO₂-eq.)	1361.47	1499.47	650.84	381.98



Figure 1. Municipal green waste is a heterogenous mixture that includes components (cut grass) for which composting is an ideal waste management strategy. There is also a woody component obtained via pruning trees and shrubs that would require additional processing (chipping) before composting becomes a viable strategy. The woody component is also likely to contain a high lignin content which will increase the time, cost and emissions of composting.

COPIAS DE CARTAS DE RESPUESTA A LAS OBSERVACIONES DE LOS REVISORES

Dear Editors,

Please find attached our revised manuscript and below our detailed explanations of how the ms has been modified in response to the critiques. We found the observations constructive and insightful and addressing these has enabled us to produce a significantly improved ms which we hope is now ready for publication in this most important of special issues. With friendly greetings, Brenton et al.

Reviewer 1, Major Comments

- My major comment concerns the quality of the carbon footprint assessment.....

In the revised version this concern has been addressed by adding extensive detail to the calculations (see the revised methods section)

- The infrastructure for all scenario

Response: we have significantly increased the amount of detail in the revised analysis, as detailed in our responses to the following observations.

- The water or other mean to "quench" the kon tiki

Response: The water used to quench the Kon-Tiki is now included in the LCA. See lines 145-146 and Table 1.

- The post processing (packing, crushing?) and transportation of the compost or biochar to place of use (that would increase their carbon footprint compared to landfill)

Response: as recommended the emissions linked to the bags needed to package the biochar and/or compost is now included in the calculations. We also added estimates of the transport emissions linked to the finished biochar and compost. See table 1 and lines 125-130 and 147-159.

- The operation for the composting procedure (needs to be moved)

Response: we are unsure how we can address this comment, or to where the reviewer recommends to move the description of the composting procedure to? At present the composting procedure, which is the basis for the carbon footprint calculations is described after the description of landfilling and before the description of biochar production, which reflects the ordering of information in Table 1.

- The associated uses (if the MGW is used for biochar production, it means that it is not used for compost production. hence the people relying on compost will need to get their nutrient from somewhere else? Mineral fertilizers perhaps, this impact severely the carbon footprint of the practice)

Response: as detailed in the discussion of the previous version of the manuscript (lines 151-155 in the revision) woody biomass is used to make biochar. Woody biomass isn't currently used to make compost in Lima, because of the additional cost associated with

chipping the relevant biomass before it can be composted. The displacement the reviewer talks about is therefore not an issue. Further rates of fertilizer and compost application to urban green space in Lima are very low. We don't have any official figures but we do work closely with the municipality of Lurin, a city of around 120,000 people. The annual budget for fertilizers, which includes compost, was around \$US 500 in 2018 (personal communication).

- Post processing (bags, pellets?) of the MGW for biochar or compost scenarios
Some of these processes may have a very small impact on the overall carbon footprint. But they should be discussed and strengthened with data and references.

Response: the carbon footprint of bags required for finished compost and/or biochar is now included. See Table 1 and response to the observation above re post processing. The numbers are based on this reference:

Ma, X., Li, C., Li, B. (2019). Carbon Emissions of China's Cement Packaging: Life Cycle Assessment. *Sustainability*, 11(20), 5554.

The biochar isn't converted into pellets.

- Similarly, I find the access to data in the manuscript very poor. Many values are not referenced or not described and appear out of the bloom (more detail in the minor comments).

Response: indeed, in the revision we have provided significantly more detail and precision. See the revised methods section and also table 1.

Minor Comments

- L.19: Can Lima still be considered "developing world context needing accessible technology"? To my knowledge continuous biochar pyrolyzer have been set up in Agua calientes, Ica, and Puerto Maldonado. Could the authors please explain why Lima would rely on small scale pyrolyzer when higher end technology is available? (<https://andina.pe/agencia/noticia-machu-picchu-is-the-most-sustainable-city-in-peru-and-latam-747731.aspx>) (<https://cincia.wfu.edu/prensa/cincia-establece-convenio-para-investigar-potencial-del-biocarbon-para-recuperar-areas-degradadas/>)

Response: the three reactors which the reviewer refers have been built with grant money, no information exists to indicate that these pilot scale plants are economically sustainable at present. Further we have expanded and made clearer the explanation /justification the reviewer correctly identified as deficient. See lines 54-61 in the revision.

- L.25: The authors use here "so called developing world" here. What do the authors mean by "so called" and why not use another word If the term is not precise enough (emergent economies? Or any other)?

Response: "so called" has been deleted from the manuscript. See line 24.

- L.32-33: Please explain how a manuscript called "Key factors determining biochar sorption capacity for metal contaminants: a literature synthesis" and another one

specifically aimed at Maize in Peru from a non-international journal attest for the clear economic value proposition biochar usage in both agriculture and soil remediation.

Response: the self-citations have been deleted and we modified the relevant text and incorporate a citation to a recent review describing the many applications or biochar being developed. See lines 32-34 in the revision.

- L.36: Does carbon in the atmosphere can really be considered a pollutant? To some extent, it has allowed life on this planet.

Response: the word pollutant has been removed from the revised version of the ms.

- L. 37: It is not just the level of CO₂ in the atmosphere but mainly the incapacity to reduce our emissions that is forcing humanity to rely on NET. See: Carton, W. et al. (2020) 'Negative emissions and the long history of carbon removal', WIREs Climate Change, 11(6), pp. 1-25. doi: 10.1002/wcc.671.

Response: we thank the reviewer for the hint and have incorporated a citation to the reference the reviewer recommends in the revision. See lines 40 – 41.

- L. 40: Not sure what "surprisingly limited" means. What was expected? Thousands of possibilities? If yes, indeed, a handful is limited. But one can also be "surprised" that such practices exist at all.

Response: in addressing the reviewer's previous point the relevant text has been deleted from the revision. See lines 40-41 for the replacement.

- L.40: About the reference to Schlesinger 2020 - Not sure citing a webinar is the right way to go. the IPCC or Pete Smith have been working on NETs or CDR for a long time. I suggest the authors to change the citation to something more timeless and peer reviewed than a webinar.

Response: as per the recommendation we've deleted the refence to Schlesinger (2020) and replaced it with:

Fuss et al. (2014). and IPCC (2018).

- L. 42: need a reference after "emissions"

Response: The following reference has been added:

Smith, P (2016) Soil carbon sequestration and biochar as negative emission technologies. Global change biology, 22(3), 1315-1324. <https://doi.org/10.1111/gcb.13178>. See line 44.

- L. 60 and 61: Sentences on waste from Lima and composted fraction need a reference.

Response: Indeed, also we noted that the passage of text as written lacked clarity which we have fixed in the revision (See lines 64 to 71). The following reference has been added:

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

- L. 62: Word urban solid waste is used for the first time. Is "urban solid waste" the same as biological waste referred to here above? If not, could you be more specific?

Response: agreed, also in revising the paragraph signaled in the previous comment we have clarified terminology in addition to reordering the text to improve clarity.

- L. 95-97: It would be appropriated to have an idea of the values here. Response: we have significantly increased the amount of detail for licensed and informal landfill in the revised analysis. 1. Instead of basing the figures on the results reported by Ziegler et al. we have generated calculations from scratch using estimates from:

Babu, G. S., Lakshmikanthan, P., & Santhosh, L. G. (2014). Life cycle analysis of municipal solid waste (MSW) land disposal options in Bangalore City. In ICSI 2014: Creating Infrastructure for a Sustainable World (pp. 795-806).

Which incidentally agree closely with the figures reported in Ziegler et al.

- L.107 - 108: Lack of many information. How did the authors calculate 32.9W? Where is the emission factor reported of electricity that allowed the authors to transform 32.9 W into 0.013 kg CO₂e?

Response: In the revised manuscript we now cite the EIA as a source, and also we have provided more detail on how the calculations were made, see line 120-123 in the revised manuscript.

- L. 112-113: $96 + 0.05 = 96.05$. Where did the 3.95% left go?

Response: this oversight has been corrected in the revision, see lines 134-136.

- L. 119-120: Maybe, but does the Kon-tiki needs only one burn to process 1000 kg of MGW? This information should be stated.

Response: this oversight has been corrected. See line 142

- L. 131-132: What is the calculation to reach the 130 kg of CO₂?

Response: We now explain with greater clarity where the figure of 130kg of CO₂eq was arrived at. See line 170-172.

- L. 132: Throughout the manuscript the authors use CO₂e, CO₂ eq, CO₂-eq, CO₂ equivalent. I suggest the authors to be more consistent in the unit chosen.

Response: We've changed the unit to CO₂eq in all the manuscript.

- **Table 1:**

- "Biomass transport emissions" has no unit

Response: We've changed the unit to kg CO₂eq. See table 1.

- The SI of kilogram is "kg" not "Kg"

Response: the suggested change has been made. See table 1.

- The sum does not add up for licensed and informal landfill. The authors should report all data with all emission factors along with their source properly cited in the reference.

Response: we have significantly increased the amount of detail for licensed and informal landfill in the revised analysis. See methods and table 1.

- Appendix: It would be more convenient is the appendix was in the same language of the main text.

Response: Unfortunately, we don't have an English version.

Reviewer #2: The work has intended to compare climate change mitigation benefits of nature-based solutions for municipal green waste in Lima city, Peru. The study has analyzed carbon footprint by managing municipal green waste under four 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. It is an important work and an excellent idea.

However, materials and methods are insufficiently described and the assumptions underlying the calculation of greenhouse gas emissions are rather generic.

Response: this comment aligns closely with the principal observations from reviewer one and in addressing reviewer ones concerns the amount detail included in the calculations has been significantly increased, see above.

There are some mistakes related to waste processing such as the belief that composting is accomplished in only 60 days. Humidification and stabilization demand longer periods to take place in a composting pile.

Response: in the revised ms we now include a citation to the work of Zhu-Baker et al 2017 to justify the figure of 60 days. We have also added an additional citation to Kuhlmann and Pace et al. to draw attention to the fact the time needed to compost can vary significantly.

I think the authors have forgotten to account for CO₂ emissions from the energy necessary to produce biochar. Temperature and resident time are other parameters missing in the manuscript:

Response: No external energy is required to pyrolyze biomass using a Kontiki oven, pyrolysis and combustion of the biomass itself provides the energy that drives the process. With regard to operating parameters during pyrolysis we agree these are

important considerations and we now discuss these in the concluding paragraph whilst also attempting to address reviewer 1s suggestion that we provide a clearer justification for why state of the art technology shouldn't be the first choice in the specific context we discuss.

VERSIÓN EN ESPAÑOL (EN CASO HAYA SIDO ACEPTADA EN OTRO IDIOMA)

La producción de biocarbón de baja tecnología podría ser una solución basada en la naturaleza altamente efectiva para la mitigación del cambio climático en el mundo en desarrollo

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Resumen

Objetivo Comparar los beneficios de la mitigación del cambio climático con soluciones basadas en la naturaleza para la gestión de residuos verdes municipales convencionales.

Métodos Este estudio analizó la huella de carbono del manejo de una tonelada de residuos verdes municipales (RVM) en Lima Perú bajo 4 escenarios diferentes: 1) Disposición final en relleno sanitario autorizado, 2) Disposición final en vertedero, 3) compostaje y 4) producción de biocarbón, utilizando un reactor Kon-Tiki de bajo costo y tecnología.

Resultados Los resultados demuestran el potencial muy claro para la mitigación del cambio climático a partir de la producción de biocarbón utilizando tecnología de baja tecnología y, por lo tanto, accesible en un contexto típico del mundo en desarrollo. La huella de carbono de la producción de biocarbón fue más baja que la del compostaje y el biocarbón y el compost tuvieron huellas de carbono significativamente más bajas que en los rellenos sanitario y los vertederos.

Conclusión Argumentamos que los estándares utilizados por las plataformas nacientes para comercializar los créditos de eliminación de carbono generados por el biocarbón deberían ablandar el requisito de tecnología para favorecer el compromiso y la participación de los participantes del mercado a pequeña escala en los países de bajos ingresos. La gestión de residuos en el mundo en desarrollo presenta desafíos importantes, pero a menudo comienza desde una base muy baja, lo que significa que existe un gran potencial para reducir las emisiones, así como para secuestrar carbono.

Palabras clave: Biocarbón, Compost, Vertedero, Residuos verdes municipales, Mitigación del cambio climático, Huella de carbono.

Introducción

Ha habido un progreso significativo en la investigación hacia el desarrollo de formulaciones de biocarbón optimizadas para fines específicos, como la inmovilización de metales pesados, el secuestro de carbono, la agronomía, como aditivo para la alimentación animal, etc. (Bolan et al. 2021). Al mismo tiempo, existe una creciente conciencia entre los científicos y los responsables de la toma de decisiones de que simplemente reducir las emisiones de gases de efecto invernadero (GEI) no será suficiente para evitar una crisis climática (Ravi et al.2016; Li et al.2019; Rogelj et al.2021).

La cantidad de carbono en la atmósfera terrestre ha alcanzado un nivel donde se ha hecho necesaria la inversión en estrategias y tecnologías que generan emisiones negativas, es decir, que reducen el nivel de dióxido de carbono en la atmósfera (Alcalde et al.2018; Mulligan et al. .2020; Carton et al.2020; EBIC 2021). Las posibilidades de hacer esto son limitadas (Fuss et al. 2014; IPCC 2018).

Sin embargo, está claro que la producción y el uso de biocarbón están listos para implementar tecnología / estrategia de gestión de la tierra que podría generar cantidades significativas de emisiones negativas (Smith, 2016). Por esta razón, ahora estamos viendo el desarrollo de plataformas comerciales para la compra y venta de créditos de eliminación de carbono relacionados con la producción de biocarbón, por ejemplo, Puro (2021) y Carbonfuture (2021).

Si bien estos avances positivos deben ser bien recibidos, es necesario perfeccionar el enfoque general para que sea más inclusivo y no excluya, por diseño, la participación de los actores del mundo en desarrollo. Las plataformas y estándares comerciales mencionados anteriormente tienden a poner énfasis en el uso de tecnología de punta para la producción de biocarbón a fin de minimizar las emisiones durante la carbonización. Esto es perfectamente razonable y factible en un contexto mundial desarrollado, donde ya existen sistemas de gestión de residuos y legislación eficaces y avanzados. En el mundo en desarrollo, la gestión de desechos a menudo comienza desde una base mucho más baja y es probable que el requisito de una gran inversión inicial actúe como una barrera para la inversión y la participación simplemente porque el entorno económico es de mayor riesgo en el mundo en desarrollo. Además, los residuos orgánicos (o "biológicos" para diferenciarlos de la etiqueta "orgánicos") suelen ser muy

heterogéneos. En los puntos de agregación de cultivos como el café y el cacao, los volúmenes de desechos pueden ser pequeños y estacionales. En estos contextos, el requisito de una inversión inicial significativa en tecnología de punta puede actuar como una barrera para la participación, aunque es posible reducir las emisiones sin la ayuda de tecnología de punta.

Idealmente, los criterios para determinar si un proyecto logra emisiones negativas y si es elegible para el financiamiento de la remoción de carbono deberían estar anclados en algo parecido al concepto de adicionalidad desarrollado por la ONU para REDD. En Perú, en el 2014 se generó un total de 7.5 millones de toneladas métricas de residuos sólidos urbanos (que incluyen orgánicos, residuos de construcción, residuos médicos, etc.); se estimó que el 47% de estos residuos terminó en vertederos (ilegales) y solo el 21% terminó en rellenos sanitarios formales (Ziegler et al. 2018). Si nos centramos exclusivamente en los residuos verdes municipales, la biomasa residual que se obtiene a través del mantenimiento regular de los espacios verdes urbanos, las cifras siguen siendo grandes. Por ejemplo, en Lima, una megaciudad de la costa peruana, vemos la generación de 1,382 toneladas de residuos verdes municipales por mes (SIGERSOL, 2021). Solo una pequeña fracción de esto se convierte en abono y la mayoría se destina a vertederos formales o informales donde los desechos verdes se descomponen en un ambiente anóxico, liberando potentes gases de efecto invernadero como el metano y el óxido nitroso (Eklund et al. 1998). En este contexto, la producción de biocarbón a partir de residuos verdes municipales en un reactor de biocarbón artesanal como un horno Kon-tiki (Ithika 2021) podría considerarse una mejora significativa con respecto al status quo. Aquí calculamos la huella de carbono del manejo de residuos verdes municipales usando cuatro estrategias diferentes: 1) disposición final en un relleno sanitario

autorizado, 2) disposición final en un vertedero, 3) compostaje y 4) producción de biocarbón utilizando tecnología artesanal de bajo costo.

Materiales y Métodos

Utilizando una tonelada de residuos verdes municipales (RVM) como unidad de análisis, calculamos la huella de carbono de la gestión de residuos verdes municipales en Lima, Perú, bajo cuatro escenarios diferentes: 1) negocio como siempre (relleno sanitario autorizado), 2) negocio como siempre (vertedero informal), 3) compostaje y 4) producción de biocarbón a través de un horno Kon-Tiki. En los cuatro casos asumimos que el contenido de carbono de la biomasa vegetal es del 50%, según IPCC (2014).

En los cuatro escenarios, la primera emisión significativa de GEI proviene del transporte de biomasa. Lima es una megaciudad y las distancias de transporte varían según la proximidad al núcleo urbano. Sin embargo, las emisiones asociadas al transporte son inevitables porque los rellenos sanitarios formales están ubicados en las afueras de la ciudad, un poco más allá de los límites de la ciudad, donde se reduce el impacto de la gestión de residuos en los residentes. Los vertederos están aún más lejos del núcleo urbano. Usando el ejemplo específico de los residuos verdes municipales de Lurín en la franja sur de Lima, asumimos la emisión de 340 g de CO₂eq emitidos por tonelada de residuos verdes municipales por km en un camión de tamaño mediano (Seo et al. 2016). En este caso específico, el cambio de vertedero a compostaje o producción de biocarbón reduce las emisiones de transporte (Tabla 1) porque la operación de biocarbón / compostaje está más cerca del núcleo urbano que los sitios de vertedero (Apéndice s1).

El paso posterior al transporte es el procesamiento de los desechos. En el primer y segundo escenario, en el que los residuos verdes municipales se eliminan en rellenos

sanitarios formales e informales, existen muchas incertidumbres en torno a la cantidad de GEI liberada de la biomasa relevante. Sin embargo, es probable que los valores sean altos ya que las condiciones anóxicas que se encuentran en el relleno sanitario favorecen la liberación de gases como el metano y el óxido nitroso (Eklund et al. 1998). La emisión de GEI (dióxido de carbono, metano y otros gases traza y partículas (CO₂, NO_x, PM_{2.5}, PM₁₀) en términos porcentuales y los multiplicadores correspondientes para convertirlos en equivalentes de CO₂ son de Babu et al. (2014), que luego se aplicaron a la línea base de 1 tonelada de residuos verdes municipales.

En el tercer escenario, en el que se compostan los residuos verdes municipales, asumimos que el 52% del contenido de carbono en la biomasa residual se retiene en el compost, según Tiquia et al. (2002). Para el 48% restante asumimos que el 3% se pierde como metano y el 45% se libera como CO₂, según Boldrin et al. (2009). Las estimaciones de CO₂eq de partículas y trazas de gases durante el compostaje se basan en Van Haaren et al. (2010). Para la producción de compost, también calculamos las emisiones que resultan del bombeo del agua subterránea necesaria para el proceso de compostaje. Idealmente, el compost debe contener un 60% de agua en peso. Suponemos que el compostaje se lleva a cabo durante 60 días (después de Zhu-Baker et al. 2017), aunque es importante señalar que el tiempo real requerido para el compostaje puede ser significativamente más corto o más largo dependiendo de la materia prima y las prácticas de manejo (Kuhlmann, 1990 y Pace et al. 1995).

Las emisiones no son la única consideración con la gestión de los productos orgánicos, el uso del agua también es fundamental, especialmente en áreas propensas a la sequía. En Lima, la tasa de evaporación es de 952,9 mm por año (MIDAGRI, s.f.). Así, un área de

2m², es decir, el área que ocuparían 1000 kg de residuos verdes municipales, requeriría 317,6 litros de agua para un compostaje óptimo. En Lurín, el agua subterránea se utiliza y se obtiene mediante una bomba de 1 caballo de fuerza. Esto, a su vez, requiere 32,9 W de electricidad, lo que da como resultado 0,13 kg de CO₂eq. Estos cálculos se basan en datos de la Administración de Información Energética de EE. UU. (EIA, 2020), que informa que se emiten 0,42 kg de CO₂eq por kWh. Suponemos que el compost producido a partir de una tonelada de residuos verdes municipales se empaqueta en 10 bolsas de plástico laminado (Tabla 1) que tienen un factor de emisión de 0.637 kgCO₂eq / bolsa (Ma et al.2019). Finalmente, una vez producido, el compost necesita ser transportado a su lugar de uso. Asumimos que cualquier compost producido será devuelto a los espacios verdes urbanos de donde se recogió la biomasa residual. Si asumimos nuevamente emisiones de 340 g de CO₂eq emitidas por tonelada, por km, para el material transportado en un camión de tamaño mediano (Seo et al.2016), llegamos a una cifra de 0.3 kg de CO₂eq de emisiones de transporte adicionales vinculadas a la gestión una tonelada de residuos verdes municipales mediante compostaje.

Finalmente, para el escenario en el que se utiliza los residuos verdes municipales para producir biocarbón, asumimos que el 30% del contenido de carbono en la biomasa de la materia prima se retiene en el biocarbón producido, según Mohammadi et al. (2016). Para el 70% del contenido de carbono de la materia prima que se pierde durante la producción de biocarbón, suponemos que el 95,6% se libera a la atmósfera en forma de CO₂, el 0,5% en forma de metano y el 3,9% como otros gases (CO, Compuestos orgánicos volátiles, NO_x y partículas), según las mediciones de Cornelissen et al. (2016). Los factores de emisión para convertir el metano y otros gases traza en CO₂eqs son de Babu

et al. (2014). También calculamos las emisiones incorporadas en el metal utilizado para fabricar un horno Kontiki. Por cada tonelada de acero producida, suponemos que se emiten a la atmósfera 1,85 toneladas de CO₂eq (Hoffmann et al. 2020). Un horno Kon-Tiki utiliza 200 kg de metal, lo que genera una emisión de 0,37 kg de CO₂eq. Cada horno tiene un ciclo de vida de aproximadamente 300 quemaduras. Cada quemadura individual consume aproximadamente una tonelada de residuos verdes municipales y produce alrededor de 320 kg de biocarbón. Por lo tanto, los 370 kg de CO₂eq incorporados en el acero utilizado para fabricar un Kon-Tiki deben amortizarse a través del biocarbón producido durante la vida útil del horno. El resultado es un nivel menor de emisiones del metal incorporado en el horno (Tabla 1). Para apagar 320 kg de biochar producido en un Kon-Tiki asumimos que se requieren 378,54 litros de agua (según McAvoy & Detternmaier, 2019).

Suponemos que el biocarbón producido con una tonelada de residuos verdes municipales está empaquetado en 6 bolsas de plástico laminado que tienen un factor de emisión de 0.637 kgCO₂eq / bolsa (Ma et al. 2019). Una vez producido, el biocarbón debe transportarse a su destino final. En Perú, el destino final más probable es San Martín, la región productora de cacao más importante de Perú. En San Martín se está utilizando biocarbón para remediar suelos con altos niveles de cadmio, en respuesta al Reglamento (CE) No 1881/2006 de la Unión Europea que prohíbe la importación de cacao que contenga más de 0.8ppm de cadmio. La distancia de Lima a San Martín es de 630km. Nuevamente asumimos 340 g de CO₂eq emitidos por tonelada de material, por km, en un camión de tamaño mediano (Seo et al. 2016). Asumimos un camión de tamaño mediano porque esos camiones traen productos agrícolas a Lima y generalmente regresan menos que llenos y podrían usarse para transportar el

biocarbón. En este escenario, el biocarbón producido a partir de una tonelada de residuos verdes municipales daría lugar a 71,5 kg adicionales de CO₂eq de emisiones relacionadas con el transporte por tonelada de residuos verdes municipales procesada.

Resultados y Discusión

El análisis de la huella de carbono en las 4 estrategias alternativas para el manejo de residuos verdes municipales sugiere que el biocarbón debería ser el método de tratamiento preferido desde una perspectiva de contabilidad de carbono, seguido del compostaje, seguido de la disposición final en vertederos autorizados o informales (Tabla 1). Si ampliamos el análisis de la huella de carbono para considerar el destino del carbono contenido en el compost y el biocarbón producido en los escenarios 3 y 4, surge una imagen ligeramente diferente. La vida media del compost puede ser tan baja como 45 días (Araújo et al. 2020). El biocarbón, por otro lado, puede persistir en el suelo durante escalas de tiempo milenarias (Spokas 2010), e incluso puede promover la acumulación de nuevo carbono no pirogénico en el suelo (Weng et al. 2017). Así, si asumimos una vida media del compost equivalente a la cifra reportada en Araujo et al. 2020, luego se liberarán a la atmósfera 130 kg adicionales de CO₂eq a partir del compost después de que hayan transcurrido dichos 45 días. La vida media del biocarbón se mide en décadas o milenios con una pérdida mínima de carbono a la atmósfera. Por lo tanto, es probable que la huella de carbono del biocarbón mejore significativamente en relación con el compost. Sin embargo, en un contexto del mundo real, tanto el compostaje como la producción de biocarbón deben considerarse sinérgicos para el manejo de residuos verdes municipales. Estos desechos tienen un componente heterogéneo que es fácil de compostar (p. Ej., Corte de césped, hojas) y complicado de

pirolizar, y un componente leñoso que es difícil de compostar, pero relativamente fácil de pirolizar (Figura 1).

La gobernanza sobre las prácticas de gestión de residuos en países en desarrollo como Perú está lejos de ser óptima. Si se requiere una fuerte inversión en tecnología de pirólisis o gasificación de vanguardia antes de que la producción de biocarbón sea elegible para créditos de carbono, entonces es muy probable que siga funcionando como de costumbre con la continuación de altas tasas de emisión de GEI de vertederos mal administrados. Creemos que los estándares incipientes para la eliminación de carbono del biocarbón deberían ampliarse para incluir tecnologías de bajo costo y poco contaminantes para permitir la participación de los actores en los contextos del mundo en desarrollo. Los cálculos de la Tabla 1 demuestran que cada tonelada de residuos verdes municipales desviada del vertedero a la producción de biocarbón artesanal reduce las emisiones de CO₂eq a la atmósfera en una tonelada. Extrapolando a la cantidad de residuos verdes municipales producidos cada mes en Lima, llegamos a una cifra de 1300 toneladas de emisiones de CO₂eq mitigadas por mes. Si luego consideramos la gestión de desechos en todas las otras megaciudades del mundo en desarrollo, donde la gestión de desechos probablemente comienza desde la misma base baja, el potencial para la mitigación del cambio climático comienza a parecer prometedor.

El desarrollo de las plataformas comerciales nacientes para las emisiones negativas generadas por el biocarbón es un avance positivo. También estamos de acuerdo en que implementar tecnología de punta es un objetivo loable que permitiría el máximo control de parámetros de producción como la temperatura. Esto a su vez permitiría la

optimización del biocarbón para fines específicos (Ippolito et al. 2020). Sin embargo, dadas las reducciones significativas de emisiones de la carbonización de baja tecnología de residuos verdes municipales sobre las prácticas actuales descritas en este análisis, argumentamos que la carbonización de baja tecnología de los orgánicos debe ser incentivada financieramente para motivar rápidamente a los operadores de gestión de residuos en el mundo en desarrollo a adoptar la carbonización como la estrategia preferida. Aprovechar los mercados emergentes de eliminación de carbono podría ser una vía eficaz para proporcionar los incentivos financieros necesarios.

Agradecimientos

Los autores desean agradecer a las siguientes personas que contribuyeron al artículo comentando los primeros borradores

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Conflicto de intereses

Los autores declaran no tener conflictos de intereses.

Tabla 1: Cálculo de la huella de carbono mediante 4 estrategias diferentes para la gestión de residuos verdes municipales. Se utilizó un multiplicador de 25 para convertir el metano en CO₂eq.

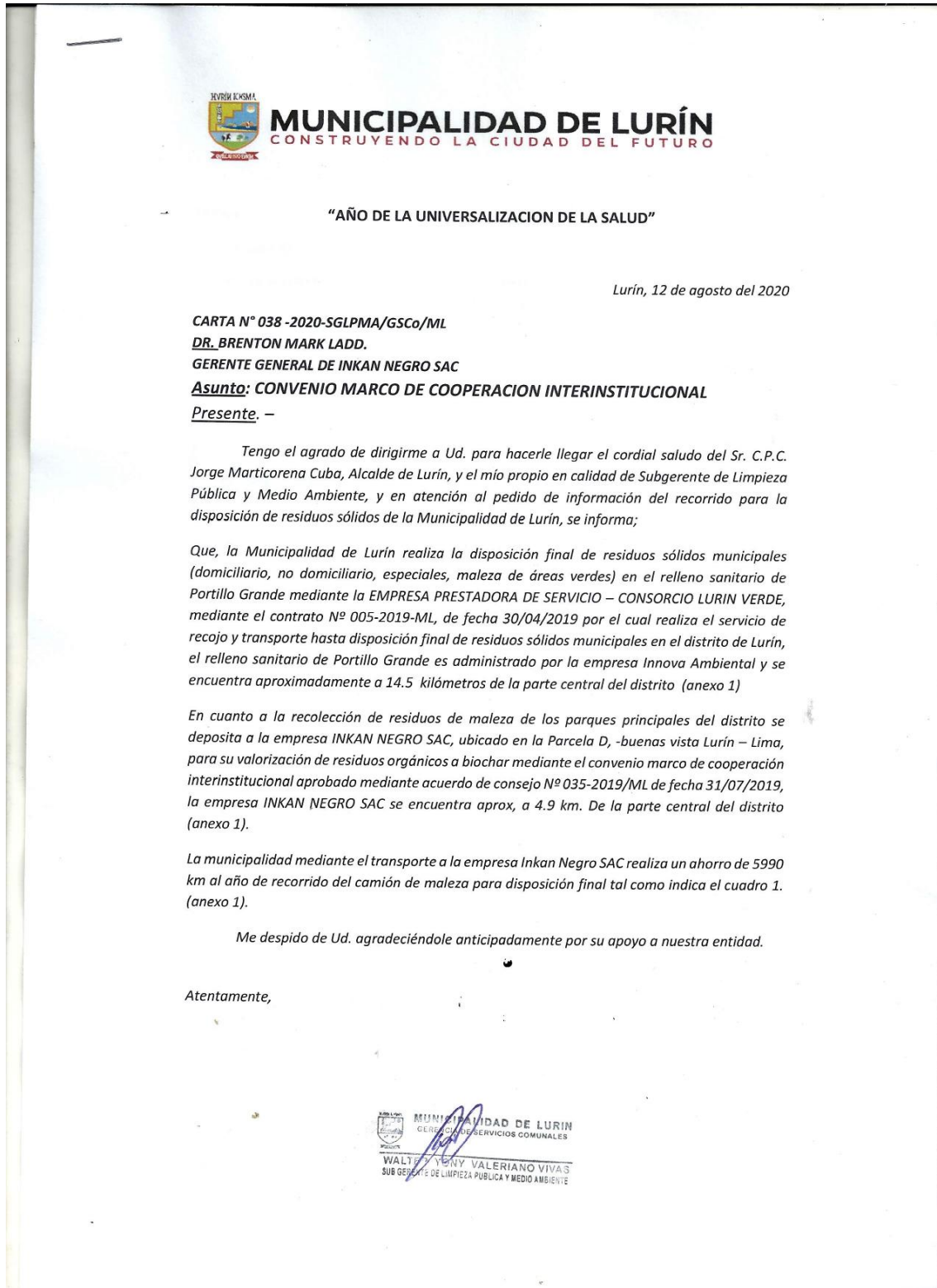
	Relleno Sanitario	Vertedero	Compost (Pilas)	Biocarbón (Kon-Tiki)
Residuos orgánicos (kg)	1000	1000	1000	1000
Contenido de carbono en 1000 kg de residuos verdes	500	500	500	500
Emisiones del transporte de biomasa	2.47	2.47	0.83	0.83
Kg de C incorporado en compost o biocarbón después del procesamiento	-	-	240.00	150.00
Kg de C liberado como GEI durante el compostaje o la producción de biocarbón	-	-	260.00	350.00
Kg de C liberado como GEI al bombear agua subterránea para compostaje	-	-	0.01	-
Kg de C liberado como GEI al bombear agua subterránea para apagar el biocarbón	-	-	-	0.307
Emisión de C por empaquetar las bolsas	-	-	6.37	3.822
Kg de C liberado como GEI para fabricar el metal necesario para construir un horno Kon-Tiki	-	-	-	0.37
Emisiones de CO ₂ de la estrategia de tratamiento de residuos	86.88	72.43	243.75	334.53
Emisiones de CH ₄ de la estrategia de tratamiento de residuos (CO ₂ eq)	1398.54	1748.18	406.25	51.82
CO ₂ eq de gases trazas y partículas (PM ₂₅ , PM ₁₀ , CO, NO _x , orgánicos volátiles, hidrocarburos)	3.87	3.87	2.028	83.77
Emisiones de transporte (CO ₂ eq) para trasladar compost o biocarbón a su destino final.	-	-	0.83	71.5
TOTAL (kg CO₂-eq.)	1492	1827	660.45	546.27

ABREVIATURAS

- GEI: Gases de efecto invernadero
- ONU: Organización de las Naciones Unidas
- REED: Reducción de Emisiones derivadas de la Deforestación y la Degradación de los bosques.
- SIGERSOL: Sistema de Información para la Gestión de Residuos Sólidos.
- RVM: Residuos verdes municipales
- CO₂: Dióxido de carbono
- NO_x: Óxidos de nitrógeno
- PM_{2.5}: Materia particulada 2.5
- PM₁₀: Materia particulada 10
- MIDAGRI: Ministerio de Desarrollo Agrario y Riego
- CO₂eq: Dióxido de carbono equivalente
- CO: Monóxido de carbono
- PPM: Partes por millón

ANEXOS

Apéndice s1





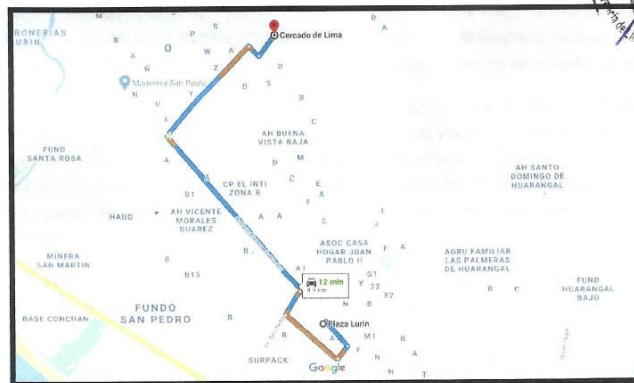
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Anexo 1

Ruta de Lurín hasta el relleno de Portillo grande



Ruta de Lurín hasta la Empresa Inkan negro SAC



Cuadro 1.-

Distancia ida y vuelta Lurín-relleno portillo grande (km)	Distancia ida y vuelta Lurín-empresa inkan negro (km)	Ahorro distancia día (km)	Ahorro distancia por semana (km)	Ahorro distancia por año (km)
29	9.8	19.2	115.2	5990

Figura 1. Los residuos verdes municipales son una mezcla heterogénea que incluye componentes (césped cortado) para los que el compostaje es una estrategia ideal de gestión de residuos. También hay un componente leñoso obtenido a través de la poda de árboles y arbustos que requeriría procesamiento adicional (astillado) antes de que el compostaje se convierta en una estrategia viable. También es probable que el componente leñoso contenga un alto contenido de lignina, lo que aumentará el tiempo, el costo y las emisiones del compostaje.



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Camila Aquije <camilaaquije97@gmail.com>

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1 mensaje

Plant and Soil Office <em@editorialmanager.com>
 Responder a: Plant and Soil Office <archie.miras@springernature.com>
 Para: Camila Aquije <camilaaquije97@gmail.com>

15 de septiembre de 2021, 12:54

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We strongly advise the authors to supply the journal with a high-resolution colour photograph related to your accepted manuscript. The best photograph amongst the papers of each volume will be featured on the cover and in the article of the printed version of Plant and Soil free of charge. Ideally, digital photographs should have a minimum resolution of 300 dpi, an image size of 15 cm x 10 cm, and saved as either tiff or jpeg file and should be sent to the Production Editor: Jill.Mortillero@springer. You will be contacted by Author Services in due course with a link to complete the grant of rights. Please note that you will receive your proofs after the publishing agreement has been received through our system.

Please remember to quote the manuscript number, PLSO-D-21-00661R1, whenever inquiring about your manuscript. With best regards,

Lucas Silva (S88), PhD
 Section Editor

Reviewer #1: The authors have replied to all my previous comments satisfactorily.

I have no other suggestions and hence recommend the manuscript for publication.

Reviewer's Responses to Questions

1. Does this paper significantly enhance our mechanistic understanding of plant-soil interactions?

Reviewer #1: No: This paper is about a LCA of biochar production and use and is not related to soil-plant interactions

Reviewer #2: Yes

2. If this paper does not enhance our mechanistic understanding of plant-soil interactions, does it shift our fundamental understanding of plant productions systems?

Reviewer #1: No:

Reviewer #2: None

3. Is this a new and original contribution?

Reviewer #1: Yes

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Reviewer #2: Yes

4. Does the title clearly and sufficiently reflect its content?

Reviewer #1: Yes

Reviewer #2: Yes

5. Are the presentation, organization and length satisfactory?

Reviewer #1: Yes

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Camila Aquije <camilaaquije97@gmail.com>

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De: Springer Nature Sharing <no-reply@email.authors.springernature.com>

Enviado: miércoles, 29 de septiembre de 2021 21:29

Para: Brenton Mark Ladd <bladd@cientifica.edu.pe>

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

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FACULTAD DE CIENCIAS AMBIENTALES
CARRERA DE INGENIERÍA AMBIENTAL

Lima, 16 de septiembre del 2021

VISTO:

El informe de revisión independiente académica del proyecto de tesis titulado: **EVALUACIÓN DEL CICLO DE VIDA DEL MANEJO DE RESIDUOS VERDES MUNICIPALES MEDIANTE LA GESTIÓN DE RELLENOS SANITARIOS, COMPOST Y BIOCARBÓN (KON-TIKI) EN LIMA**, presentado por:

- **Camila Alessandra Aquije Ramos**

CONSIDERANDO:

Que, de acuerdo al Reglamento General de la Universidad Científica del Sur y los reglamentos de pregrado para obtener el título profesional de **Ingeniero(a) Ambiental** en la **Facultad de Ciencias Ambientales**, se debe desarrollar un trabajo de investigación.

Que, de acuerdo a la normativa vigente de la Universidad Científica del Sur, en uso de las atribuciones conferidas al Director Académico de Carrera.

SE RESUELVE:

Aprobar e inscribir el proyecto de tesis titulado: **EVALUACIÓN DEL CICLO DE VIDA DEL MANEJO DE RESIDUOS VERDES MUNICIPALES MEDIANTE LA GESTIÓN DE RELLENOS SANITARIOS, COMPOST Y BIOCARBÓN (KON-TIKI) EN LIMA** con N° de registro: 316-2021-PRE11, y establecer el inicio del periodo de ejecución del mencionado proyecto.

Nombrar al docente/colaborador **Brenton Ladd** como asesor(a) para el desarrollo de la tesis en cuestión.

Regístrese, comuníquese y archívese,



Mg. Gonzalo Francisco Flores Roca
Director Académico
Carrera de Ingeniería Ambiental

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