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Efficiency of Plant Biomass Processing Pathways for Long-Term Soil Carbon Storage

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ABSTRACT

The potential for soil carbon (C) sequestration strongly depends on the availability of plant biomass inputs, making its efficient use critical for designing net zero strategies. Here, we compared different biomass processing pathways and quantified the long-term effect of the resulting exogenous organic materials (EOMs) to that of direct plant residue input on soil organic carbon (SOC) storage. We estimated C losses during feed digestion of plant material, storage of manure, composting and anaerobic digestion of plant material and manure, and pyrolysis of plant material, using values reported in the literature. We then applied an extended version of the widely used SOC model RothC with newly developed parameters to quantify the SOC storage efficiency, that is, accounting for both processing losses off-site and decomposition losses of the different EOMs in the soil. Based on simulations for a 39-year long cropland trial in Switzerland, we found that the SOC storage efficiency is higher for plant material directly added to the soil (16%) compared to digestate and manure (3% and 5%, respectively). For compost, the effect was less clear (2%–18%; mean: 10%) due to a high uncertainty in C-losses during composting. In the case of biochar, 43% of the initial plant C remained in the soil, due to its high intrinsic stability despite C-losses of 54% during pyrolysis. To provide robust recommendations for optimal biomass use, it is essential to consider additional factors such as nutrient availability of EOMs, environmental impacts of soil application, and life cycle assessments for the entire production processes.

1 | Introduction

Soil organic carbon (SOC) accrual has the potential to reduce atmospheric CO_2 concentrations because CO_2 taken up during photosynthesis by plants can partly be stabilised in the form of SOC during/after biomass decomposition and be stored in the soil for decades or centuries (Lal 2004; Smith 2016). However, in order to increase SOC storage, we need to improve our understanding of how to make best use of the available plant biomass, a finite resource. A key question is whether leaving plant material on the field maximises SOC storage or if processing biomass, such as through composting or pyrolysis, leads to greater long-term C retention. The step of processing allows additional valorization of the biomass (e.g., feed or energy production), and converts the initial plant material into a more stable form (e.g., manure or compost). However, part of the C is lost

Summary

- How to make best use of biomass for long-term soil organic carbon (SOC) storage remains unclear.
- More stable organic matter is formed during processing/storage of plant material or animal excreta.
- Effects of different stabilities on SOC were quantified considering also C losses during processing.
- Efficiency for SOC storage increased from digestate/manure to compost, plant material up to biochar.

during conversion, possibly resulting in a lower SOC storage efficiency. Previous research has indicated that about 13% of the C initially present in plant material remains in the soil for several decades, regardless of whether the material is applied directly or after undergoing various biological processes, for example, animal digestion followed by application as excreta, or plant material and excreta that underwent anaerobic digestion before being added to the soil (Thomsen et al. 2013). Because different processes generate exogenous organic material (EOM) with different intrinsic biological stability (Lehmann et al. 2021; Levavasseur et al. 2021), these results point towards a trade-off between stabilisation during processing and mineralization in the soil (i.e., more stable but smaller amounts of C remain).

In the present conceptual study, we used an extended version of the SOC model RothC (Coleman and Jenkinson 1996; Keel 2023) with newly developed parameters for different types of EOM (Leifeld et al. 2024) to estimate their long-term effect on SOC storage. The first analysis assessed the impact of EOMs with varying stabilities on SOC stocks by adding equal amounts of EOMs to the soil and quantifying the SOC increase with RothC. In a second analysis, we expanded the first analysis by additionally accounting for the efficiencies of biomass processing pathways for long-term SOC storage. In contrast to using equal amounts of EOMs, we estimated the amount of C retained as EOM after processing identical quantities of the original plant material through various methods using literature data. The application of these differing amounts of EOM to the soil was simulated with RothC to quantify the SOC increase using the same parameters as in the first analysis. Finally, the SOC change was expressed relative to the initial amount of C in the plant raw material. Most previous studies (with the exception of Thomsen et al. 2013) have compared the effect of EOMs on SOC storage without specifying the amount of C in the initial plant material (e.g., Johnston et al. 2009; Kätterer et al. 2014). Such studies focus on the different stabilities of EOMs (as in our first analysis) but are not appropriate for comparing SOC storage efficiencies, as they do not account for the varying amounts of C that were lost during processing. In contrast, our results are useful in the context of climate change mitigation, as they show how biomass use in agriculture can be optimised to maximise long-term C storage in the soil.

2 | Materials and Methods

To compare long-term SOC storage for annual additions of plant material, manure, compost, digestate and biochar, we used a version of RothC that included two EOM pools (Mondini et al. 2017; Keel et al. 2023; Keel 2023) in addition to the five pools of the original version (Coleman and Jenkinson 1996; Data S1). The SOC evolution of the topsoil (0–30 cm) was simulated for a single field from a long-term cropping trial in Switzerland that received only mineral fertiliser (Maltas et al. 2018). The crop rotation was composed of different cereals and rapeseed, the majority of aboveground residues were removed and the soil was regularly tilled. This management represented the baseline scenario and resulted in a SOC stock decrease of 11.4 t ha^{-1} between the year 1976 and 2014. Such losses of SOC are common in long-term experiments in Switzerland (Keel et al. 2019). More details about the field trial, crop rotation and management are provided in the Data S1.

For our first analysis considering varying stabilities of different EOM amendments, we assumed that 2 t C ha^{-1} of different forms of EOM were added per year in addition to plant C inputs from crop residues. To keep the study simple, we did not specify the type of plant material used to produce EOM. Because RothC is a pure C model, the entire study is based on C units. Whether EOMs are added on the soil surface or are mixed into the topsoil cannot be considered in RothC, but the latter has shown to increase SOC storage (Gross and Glaser 2021). For compost, digestate and manure, the mean parameters given in Leifeld et al. (2024) were used. These parameters include both the partitioning of C between a more labile and a more stable EOM pool, as well as their corresponding decomposition rate constants. Upper and lower ranges for each parameter were used to estimate confidence intervals.

For our second analysis focusing on SOC storage efficiency, loss rates of C for different biomass processing methods were gathered from the literature (Table S1). Remaining amounts of EOM-C were calculated (Table S2) assuming an initial amount of 2 t C $ha^{-1} year^{-1}$ of plant material was available (without exactly specifying what type of material). In the case of anaerobic digestion and composting, two types of feedstocks were distinguished: Plant material and excreta. The final amounts of EOM-C remaining as a result of the different processing methods ranged from 10% (feeding followed by anaerobic digestion of excreta) to 100% (plant material directly added to soil) (Figure 1). For simulations with RothC, we applied these different amounts of EOM that ranged from 0.13 to 1.88 t C $ha^{-1} year^{-1}$ (Table S2, last column). To simplify the study, feedstocks (i.e., plant material and manure) were no longer distinguished for simulations with RothC in the case of digestate and compost, and average C inputs were used (0.31 and 0.79 t C $ha^{-1} year^{-1}$ for digestate and compost, respectively) and combined with mean parameters given in Leifeld et al. (2024). To calculate confidence intervals, the highest C inputs were combined with parameters describing the highest stability of EOMs, and the lowest C inputs were combined with the lowest EOM stabilities (Data S1).

3 | Results

Annual additions of 2 t C ha^{-1} of EOM-C increased SOC stocks relative to the baseline for all types of organic matter inputs (Figure 2). Averaged over the first decade, increases ranged from 0.61 t C $ha^{-1} year^{-1}$ in the case of plant material to 1.9 t C

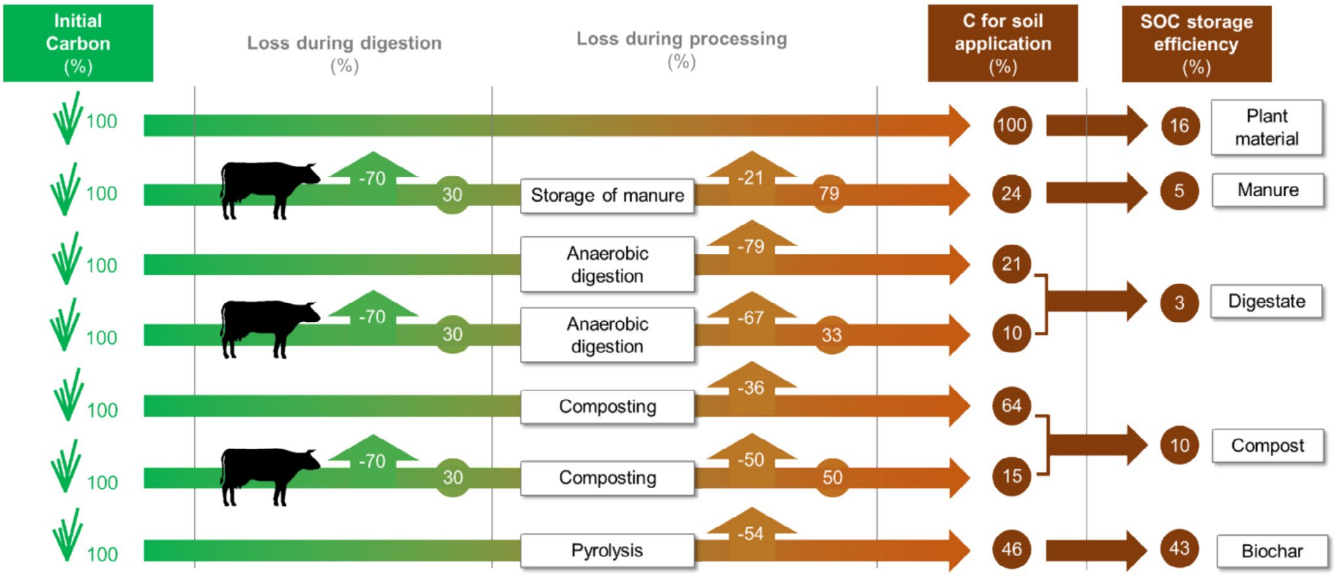

FIGURE 1 | Carbon losses during processing of plant material that were considered in this study. All values are from the literature (Data S1). The SOC storage efficiency was calculated based on the ratio of SOC stock increases quantified using the SOC model RothC and the initial amount of C in plant raw material. For the simulations with RothC we no longer distinguished whether plant material or excreta were anaerobically digested or composted and used average values.

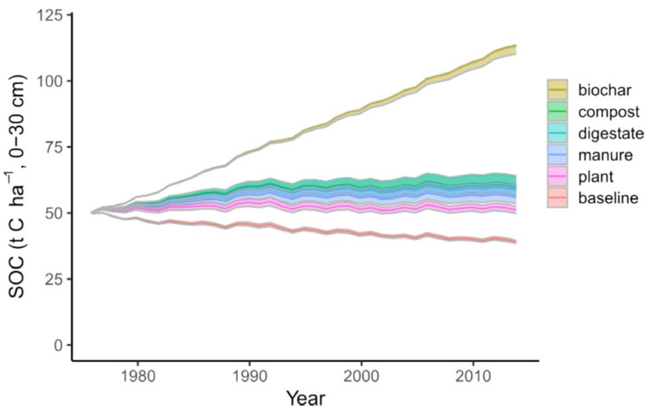

FIGURE 2 | Results of the first analysis presenting the change in soil organic carbon (SOC) stock due to annual additions of 2 t C ha^{-1} in the form of different EOMs in addition to only crop residues (baseline) for a Swiss cropland site. Shading represents the area between the upper and lower confidence intervals (reflecting the parameter range).

ha^{-1} year^{-1} for biochar (Table 1). Except for biochar, SOC stock increases diminished with each decade and from the third decade onward, average changes were smaller than the standard deviations across 10 years. For biochar, average SOC increases over all years (i) were 3.5 to 6.3 times higher than for the other EOMs, (ii) remained constant over time and (iii) had standard deviations that were less than half of those for the other EOMs. These different patterns can be explained by the high stability of biochar, with the labile fraction being on average less than 2% and a mean residence time of 1250 years for the stable pool (Rodrigues et al. 2023).

The second analysis that accounted for C losses from processing 2 t C ha^{-1} of plant material (i.e., resulting in different amounts of C inputs used for SOC modelling; Figure 1 and Table S2, last column) also showed the highest SOC increases for biochar (Table 2). These increases remained relatively constant over time, and variations between decades could be explained by temporal changes in the amount of crop residues in the baseline scenario that were added in addition to biochar. For other EOMs, SOC

TABLE 1 | Results of the first analysis representing mean SOC changes (t ha^{-1} year^{-1}) for 0–30 cm depth relative to the baseline for four different decades (last period is only 8 years long) and all 39 years in response to annual additions of 2 t C ha^{-1} in the form of different types of EOM. Standard deviations were calculated over the number of years.

	Change in SOC (t ha^{-1} year^{-1}) for equal amounts of EOM added				
Year	**Plant Mean ± SD**	**Manure Mean ± SD**	**Digestate Mean ± SD**	**Compost Mean ± SD**	**Biochar Mean ± SD**
1977–1986	0.61 ± 0.26	0.84 ± 0.25	1.04 ± 0.27	1.08 ± 0.28	1.90 ± 0.12
1987–1996	0.25 ± 0.28	0.42 ± 0.24	0.53 ± 0.28	0.55 ± 0.29	1.97 ± 0.08
1997–2006	0.22 ± 0.25	0.27 ± 0.23	0.32 ± 0.26	0.33 ± 0.28	1.97 ± 0.07
2007–2014	0.11 ± 0.26	0.15 ± 0.27	0.17 ± 0.30	0.17 ± 0.32	1.93 ± 0.08
1977–2014	**0.31 ± 0.31**	**0.43 ± 0.35**	**0.53 ± 0.42**	**0.55 ± 0.44**	**1.94 ± 0.09**

TABLE 2 | Results of the second analysis showing mean SOC changes (t ha^{-1} year^{-1}) for 0–30 cm depth relative to the baseline for four different decades (last period is only 8 years long) and all 39 years in response to annual additions of different types of EOM. The amount of C added to the soil (values in last column of Table S2) varied depending on the loss rates during feeding and processing, but was estimated based on the same initial amount of plant material (2 t C ha^{-1}). Means are presented with standard deviations calculated over the number of years.

	Change in SOC (t ha^{-1} year^{-1}) for different amounts of EOM added				
Year	**Plant Mean ± SD**	**Manure Mean ± SD**	**Digestate Mean ± SD**	**Compost Mean ± SD**	**Biochar Mean ± SD**
1977–1986	0.61 ± 0.26	0.15 ± 0.08	0.10 ± 0.07	0.39 ± 0.12	0.84 ± 0.08
1987–1996	0.25 ± 0.28	0.10 ± 0.06	0.08 ± 0.06	0.21 ± 0.10	0.90 ± 0.08
1997–2006	0.22 ± 0.25	0.06 ± 0.06	0.05 ± 0.06	0.13 ± 0.10	0.90 ± 0.07
2007–2014	0.11 ± 0.26	0.04 ± 0.08	0.03 ± 0.07	0.07 ± 0.13	0.89 ± 0.05
1977–2014	**0.31 ± 0.31**	**0.09 ± 0.08**	**0.07 ± 0.07**	**0.21 ± 0.16**	**0.88 ± 0.07**

stock increases were highest after the addition of unprocessed plant material for all decades separately and also averaged over all years (Table 2; Figure 3). After 39 years, SOC stocks in treatments with plant addition were 12 t ha^{-1} higher compared to the baseline, whereas additions of manure or digestate only resulted in mean SOC increases of 2.6–3.5 t ha^{-1} (Table 3). Differences in SOC increases between additions of plant material and compost were less evident (range of 10.7–13.5 t C ha^{-1} for plant material vs. 1.5–14.3 t C ha^{-1} for compost; ranges reflect parameter range) due to the lower and highly variable C losses during composting (Table S1) and the higher stability of compost. The mean increase in SOC was twice as high for compost compared to manure and digestate (Tables 2 and 3). The amount of C that remained in the soil after 39 years relative to the initial amount of unprocessed plant material ranged from 3% to 5% for digestate and manure to 43% for biochar with intermediate values (10%–16%) for compost and plant material (Table 3).

4 | Discussion

We found that the SOC storage efficiency was higher for plant material left on the field compared to plant material that was first digested by animals and/or in biogas plants before being added to the soil as manure/digestate. Differences in SOC storage efficiency between plant material and compost were less clear. For manure and digestate, this means that C losses during processing are not compensated by the higher stability of the resulting EOM compared to plant material. These results differ from an earlier study which showed that 12%–14% of plant material was stabilised in the soil for three different processing pathways: feeding it to animals, anaerobic digestion of plant material, and anaerobic digestion of excreta (Thomsen et al. 2013). Since the loss rates during cattle feeding were assumed to be the same as in Thomsen et al. (2013), the differences can only be explained by differences in loss rates during storage/digestion of manure or after application to the soil. In the case of manure, the most likely explanation for the lower amount of C retained in the soil in our study is that we account for C losses in the range of 13% to 28% during storage prior to field application (Wüst-Galley et al. 2020; Table S1). Storage is often needed to apply manure at the time when crops require fertilisation, to avoid winter application and thus nitrogen (N) leaching, and to collect sufficient material prior to field application (Kupper et al. 2020). Expressing SOC changes for manure relative to EOM amounts added (as calculated from Table 3) allowed a comparison of the manure-C retention coefficient with a meta-analysis (Maillard and Angers 2014). Our estimated range (14%–28%; mean: 19%) overlaps with their range (8%–16%; mean: 12%) that is based on long-term experiments with an average duration of 18 years, but our values are at the upper limit. Their global estimate included studies from the tropics, where SOC increases were lower, possibly explaining the slight discrepancies. However, it is also possible that RothC overestimates C retention in the soil as several factors such as erosion are not accounted for. Generally, it is important to note that relevant soil processes such as aggregation or carbon-nutrient interactions are also not implemented in RothC.

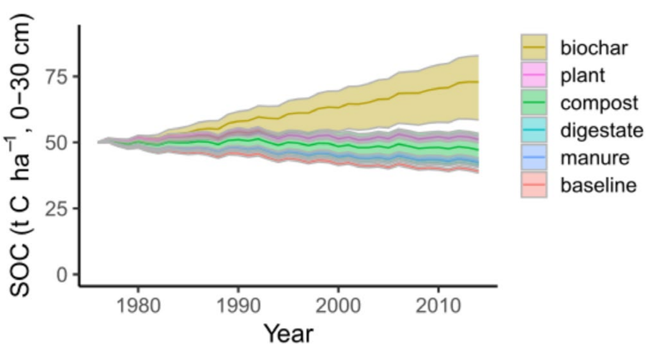

FIGURE 3 | Results of second analysis showing the change in soil organic carbon (SOC) stock for a Swiss cropland site assuming 2 t plant material-C ha^{-1} year^{-1} were processed (i.e., digested/stored/pyrolyzed) and remaining amounts (0.13–1.88 t C ha^{-1}; Table S2) were added to the soil or added directly as plant material (2 t C ha^{-1}). The baseline received only crop residues. Shading represents the area between the upper and lower confidence interval (reflecting the parameter range).

In the case of digestate, several assumptions between the present study and that of Thomsen et al. (2013) varied and likely contributed to the differences. First, we used higher loss rates during digestion of excreta (67% compared to 53% in Thomsen et al. (2013)). Second, we applied a different approach to estimate the long-term storage of C in the soil. Thomsen et al. (2013)

TABLE 3 | Results of the second analysis showing total amounts of EOM-C that remained after processing and were added to the soil during 39 years. Respective mean increases in SOC stocks (ΔSOC) after 39 years, relative to the baseline, are shown as absolute values and in percent of initial amounts in plant material (confidence intervals based on parameter range are shown in brackets).

EOM type	Total amount of EOM added (t C ha^{-1})	Total ΔSOC (t C ha^{-1})	ΔSOC as percent of initial plant C (%)
Plant	78.0	12.1 [10.7; 13.5]	15.5 [13.7; 17.3]
Manure	18.3	3.5 [2.6; 5.1]	4.5 [3.4; 6.5]
Digestate	11.7	2.6 [1.8; 3.9]	3.3 [2.3; 5.0]
Compost	30.8	8.1 [1.5; 14.3]	10.4 [1.9; 18.4]
Biochar	35.9	33.8 [19.5; 43.8]	43.4 [24.9; 56.1]

used incubation experiments to estimate C losses during the first 2 years after addition of EOM to the soil, and then assumed that what remained in the soil was stabilised. We employed the model RothC and directly estimated the C remaining in the soil as the difference in SOC between a 39-year simulation, where C was added as digestate and a baseline simulation.

In the present study, the results for compost were more similar to plant material and the amount of plant-derived C retained in the soil was twice as high compared to manure/digestate (Table 3). It is important to note, though, that the uncertainty range for compost was large, ranging from 2% to 18%, and was mainly due to a large range in C losses during processing. Many factors affect these loss rates, such as the composting time, experimental scale or the moisture content. Furthermore, the type of feedstock and its C/N ratio are important factors. These are also relevant for other processing pathways such as anaerobic digestion or digestion by animals. That we did not specify the type of plant material used is a limitation of this work and should be accounted for in future studies. Despite high C losses of 54% during biochar production, higher amounts of C remained in the soil compared to all other EOMs. This was expected because of the very low decomposition rates and agrees with observations reviewed by Wang et al. (2016) and previous modelling studies (Lefebvre et al. 2020; Pulcher et al. 2022; Andrade Díaz et al. 2023). Thus, the trade-off between off-site stabilisation (i.e., C loss during conversion of plant material to biochar) and in-soil mineralization (i.e., reduction of SOC mineralization rate due to higher stability of added biochar) does not compromise the use of biochar for long-term soil C storage.

The results presented here are for a single site in Switzerland. Although similar results are expected for other pedo-climatic regions, an important next step would be to expand this study to a spatial scale. For France, Andrade Díaz et al. (2023) showed that changes in SOC were strongly region-specific, not only because of environmental conditions, but also because the amount of available plant material varied due to the spatial distribution of those crop types that provide high amounts of residues.

5 | Conclusions

In terms of SOC storage efficiency, our conceptual study suggests that adding plant material directly to the field is better than converting it to more stable forms of organic matter through anaerobic digestion or digestion by animals beforehand. For compost, the difference is less clear because C losses during processing are lower and highly variable as they depend on many factors. Biochar, however, clearly outperforms the addition of plant material and the other studied processing pathways regarding the amount of C retained in the soil over several decades. For practical recommendations, additional factors should be considered, such as the quality of the initial plant material, nutrient availability of EOMs, effects on soil biota and environmental effects during processing, storage and soil application, including nutrient leaching and gaseous emissions. Some of these factors depend on pedo-climatic conditions, and hence it is crucial to account for local circumstances. Furthermore, we suggest complementing this information with full life cycle assessments that consider the energy costs for transport of biomass, the energy savings from fossil fuel substitution by biogas, and the additional benefits of energy or animal production when plant material is used for anaerobic digestion or animal digestion rather than direct field application.

Author Contributions

Sonja G. Keel: conceptualization, writing – original draft, visualization, writing – review and editing, data curation, formal analysis, methodology. **Alice Budai:** writing – review and editing. **Lars Elsgaard:** writing – review and editing. **Brieuc Hardy:** writing – review and editing. **Florent Levavasseur:** writing – review and editing. **Liang Zhi:** writing – review and editing. **Claudio Mondini:** writing – review and editing, validation. **César Plaza:** writing – review and editing. **Jens Leifeld:** conceptualization, funding acquisition, writing – review and editing, project administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.