

Article

Carbon Sequestration in Support of the “4 per 1000” Initiative Using Compost and Stable Biochar from Hazelnut Shells and Sunflower Husks

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Abstract: The achievement of carbon neutrality till 2050 will require the deployment of negative carbon emission technologies like the production and soil incorporation of biochar, produced from pyrolyzed plant-based residues. The carbon sequestration potential of biochar (BC) from hazelnut (*Corylus avellana* L.) shells (HNS) and sunflower (*Helianthus annuus* L.) husks (SFH) was evaluated when the biomass was carbonized in a fixed bed reactor, in a rotary kiln and in a screw reactor. In all tested reactors, higher temperatures (>500 °C) and longer retention times increased the C concentration and stability of the biochar, with negligible effects of the reactor type and feedstock. A national case study was developed for Austria concerning the potential use of SFH- and HNS-BC in combination with compost for reaching the “4 per mille” objective. An annual soil organic carbon increase of 2.5 Mt C would be needed, requiring amendment rates of 2.2 Mt C a^{−1} for all annual crop areas and 0.3 Mt C a^{−1} for all vineyards and orchards. If compost only were used, the annual cost would be about 200 EUR ha^{−1} but short-term re-mineralization would have to be considered. If the more recalcitrant biochar were used only, about 2.3 t BC ha^{−1} would be needed at a cost of 1400–1870 EUR ha^{−1}. The study shows in principle the feasibility of applying compost–biochar mixtures for achieving the “4 per mille” objective but in practice, supplemental soil management strategies for sequestering C will be required.

Keywords: soil organic carbon (SOC); pyrolysis; screw reactor; rotary kiln; fixed bed reactor

1. Introduction

Many different approaches to abate climate change and its consequences are under investigation. The deployment of negative emission technologies (NETs) is considered indispensable to reach the 2 °C goal [1]. Compared with other NETs, such as afforestation, bioenergy with carbon capture and storage (BECCS) or direct air capture of CO₂, soil carbon sequestration (SCS) and amendment of biochar (BC) have a smaller, but significant negative emissions potential, namely 0.7 Gt Ceq./a, but fewer potential disadvantages such as high energy or water consumption or land requirement [1]. Sequestering C in soil in order to drastically delay and mitigate its release to the atmosphere reduces carbon dioxide emissions and can lead to increased soil organic carbon (SOC) and therefore contribute to enhanced soil fertility and crop production [2]. The so-called “4 per 1000” initiative, which was launched by the 21st Conference of the Parties (COP21) suggests an annual increase in SOC stocks of 0.4% of the current stocks in the top 30–40 cm soil of all land covers around the world. Minasny et al. [3] emphasized that soils with low initial SOC under 30 t C/ha in the topsoil could even sequester annual rates of up to 1%.

Various methods such as minimum tillage or no-tillage systems, permanent crop covers and optimized crop rotations, crop species with extensive root systems, crop residue incorporation into soil, mulching, intercropping, composting, afforestation and reforestation, restoration and protection of histosols and the soil amendment of biochar are considered as possible ways to improve SOC stocks [4].

A long-term study [5] reported that the incorporation of manure and of compost are the agricultural practices with the highest potential for C enrichment with +267 kg C/ha~30 cm for manure and +620 to 1400 kg C/ha~30 cm for compost annually. According to a national guideline for the use of biogenic compost in Austria [6], the maximum annual amount of adding dry compost to agricultural soils is 8 t/ha, for vineyards it is 40 t/ha within five years and for the re-cultivation of degraded soils, 160 t/ha can be added within 20 years.

However, this kind of soil amendment is effective only until sink saturation is reached in soils, implying a potential decrease in the effectiveness of this practice after 10–100 years, depending on soil type, climate zone and type of amendment [1]. Therefore, it is crucial to focus on soils with low initial SOC stocks and on the carbon stabilization in the soil, since organic matter added to the soil is typically available for soil microorganisms and finally is degraded to CO₂ [2].

Considering that adding BC to the soil increases SOC with recalcitrant organic carbon which is not fully available for microorganisms and even suppresses the mineralization of labile organic matter in the long run via the so-called negative priming effect [7], it could play a major role in C sequestration scenarios in order to mitigate climate change. Even though the amendment of fresh BC may lead to positive priming in the early phase of incubation [8], various studies showed a clear dominance of negative priming in the long-term [7]. Ding et al. [9] reported that only BC with low C or high N content or BC derived from sludge caused positive priming especially in dry and C-poor soils, but other types of BC exhibited negative priming. Hence it is crucial that the BC production process is optimized towards high carbon content and high stability if C sequestration is the main aim of adding biochar to soil.

The stability of BC contributes to a much longer residence time in soil than compost. Its resistance to mineralization may persist for more than 500 years, with a turnover rate of 0.0046%/d of 97% of the BC carbon [7]. The labile pool is mineralized much faster and therefore it is not considered for further estimations. Further, potential soil erosion might influence a loss of BC [10], but this was not taken into account for the estimations since most Austrian soils are protected by minimum tillage or greening measures, supported by corresponding agricultural policy.

The recalcitrance of compost is much lower compared with BC, depending on different factors like input material, composting process type and age [11]. Especially in the first phase after incorporating compost into soil, high mineralization rates have been reported, mainly depending on compost type, stability and soil conditions. Lim et al. [12] observed that in the first hundred days after incorporation, 1.6–11.4% of the TOC contained in different types of compost were mineralized. Eghball [13] showed that after four years of compost application, only 36% of the compost-C was left in the soil. Hence, the C sequestration potential of compost might be high, but only for the short-term. Based on the findings of [12,13], mixtures with BC could play a larger role for long-term carbon sequestration because of the longer C retention times of the condensed aromatic molecular structure of BC [14].

Among the multitude of biomass materials appropriate for pyrolysis, those waste materials that have no other high-value usage are the most efficient input materials. This study focused on two residues that are either burnt or left to rot: sunflower husks and hazelnut shells. Sunflower husks are a major residue of sunflower production with about 21–30% of hulls in relation to seed weight [15]. Hazelnut shells were selected as their proportion of residues are even higher (50–60% of nut weight, [16]) and Chile, where the experimental part of this study was performed, is the major hazelnut exporting country in the Southern Hemisphere. This study had the objective to provide proximate and ultimate analysis results and to determine the elemental composition (C, H, N, O) of differently produced BC as the most relevant parameters for BC stability in soil. In order to evaluate the feasibility of reaching the 4 per mille objective by enhanced carbon sequestration with organic soil

amendments, exemplary analyses of biochar from different production processes using hazelnut shells (HNS) and sunflower husks (SFH) as feedstock were carried out. Based on these results, the necessary amounts of BC and compost were estimated to achieve the 4 per mille objective with this management strategy for soils in Austria as a national case study. Additionally, the economic efficiency of the use of compost and/or the analyzed biochar for achieving the respective carbon sequestration objective was assessed.

2. Materials and Methods

2.1. Feedstock

For the pyrolysis experiments in a fixed bed reactor and a rotary kiln, *Corylus avellana* L. (hazelnut) shells were obtained from the company “Agrichile” situated in Central Chile. The shells were ground and sieved to a particle size of 1–2 mm, the water content was between 6 and 10%.

For the pyrolysis experiments with a screw reactor, *Helianthus annuus* L. (sunflower) husks were obtained from the vegetable oil-producing company “Bunge Austria” in Lower Austria. Annually, around 9000 t of sunflower husks are by-products of Bunge’s sunflower oil production. That means that significant amounts of this biomass are available in pure form and with low material collection and transport efforts.

2.2. Experimental Set-Up

2.2.1. Fixed Bed Reactor

In order to produce BC and biooil, a fluidized bed reactor (Figure 1a), situated at the Unidad de Desarrollo Tecnológico (UDT) in Coronel, Chile, was operated on the laboratory scale batchwise in fixed bed mode at different temperatures. For the experiments, all component parts of the condenser and the electrostatic filter were weighed. Then, 10 g of hazelnut shells was filled into the tube reactor (2) from the top. All heated parts were insulated with mineral insulation material. The inner diameter of the tube reactor was 37.5 mm and the length 270 mm. The feedstock was located on a grid in the bottom part of the tube. In order to remove oxygen from the system, it was flushed with 1 l/min nitrogen (99.995%) for 10 min before the experiment. Then, the cooling water for the condenser (5) was chilled to 4 °C with a cryostat. While the nitrogen flow was left unchanged in order to act as an inert carrier gas for the volatiles, an experimental run was started by turning on the furnace (3), the heating for the hot gas filter (4) and the electrostatic filter (6). The furnace control unit was set to a heating rate of 10 °C/min to the desired temperature (350, 400, 500, 600 °C) and maintained for 30 min. During a run, all temperatures were monitored every 5 min manually. Bio-oil was collected in the bottom parts of the condenser (5) and the electrostatic filter (6). The residual volatiles were not collected separately. When the run was finished, the biochar was left on the grid in the reactor (2). Finally, all samples were collected and weighed.

2.2.2. Rotary Kiln

A rotary kiln on the pilot scale (280 mm diameter and 3000 mm length) was used to produce BC and bio-oil (Figure 1b). The feedstock was located in a reservoir which was connected to a rotary feeder that moved it on to the auger. An amount of 44 kg of hazelnut shells with a water content of 12% was fed to the reactor by the auger with an average input rate of 13.2 kg/h. It was heated indirectly by a manually controlled liquid gas burner. In order to move the feedstock through the reactor, it was inclined at an adjustable angle while the reactor rotated and transported the BC into a collecting vessel. The pyrolysis gas was transported to a condensation system where bio-oil was precipitated from the gas. The reaction time was 200 min.

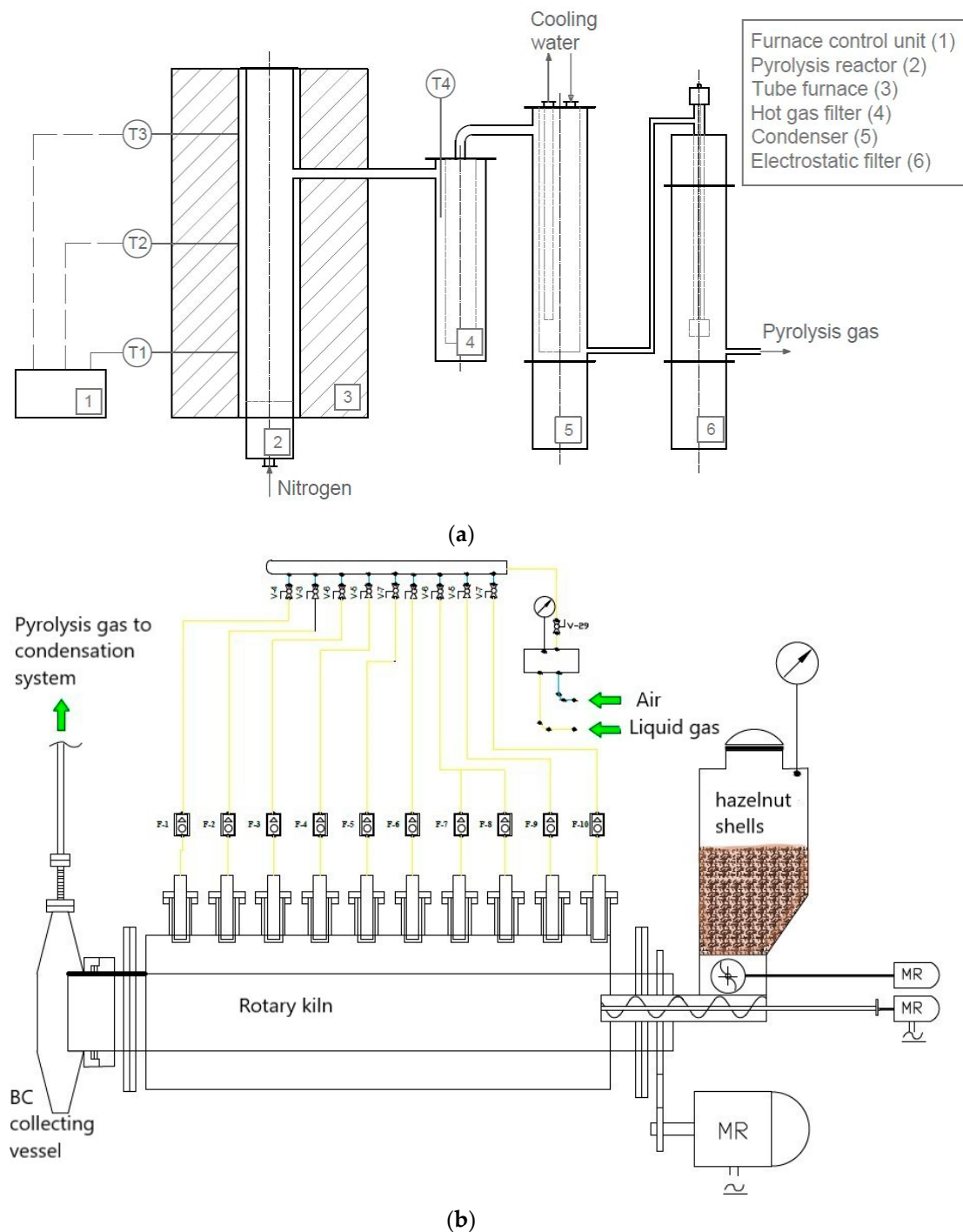


Figure 1. (a) Schematic sketch of the fixed bed reactor used for the pyrolysis of hazelnut shells (top); (b) schematic sketch of the rotary kiln used for the pyrolysis of hazelnut shells (MR ... gear motor, F_i ... flowmeter, V_i ... valve) (bottom).

2.2.3. Screw Reactor

To produce BC from sunflower hulls (SFH), a screw reactor was operated on the laboratory scale (Figure 2). The rotary feeder was purged with a nitrogen flow of 5 L/min during the whole experiment, while the SFH were transported into the oxygen-free screw reactor. Via electric heating coils, the reactor was indirectly heated up to the desired process temperatures (400 and 600 °C). Negative pressure forced the volatile matter into the combustion chamber where it was burned and released to the environment because the main purpose of the reactor was the production of BC. The emerging BC was discharged

into a collecting vessel. In order to prevent the re-condensation of polycyclic aromatic carbohydrates in the BC, the temperature of the end part of the reactor was kept at $>300\text{ }^{\circ}\text{C}$. The tested residence times of the SFH during the experiments were 10 and 30 min each.

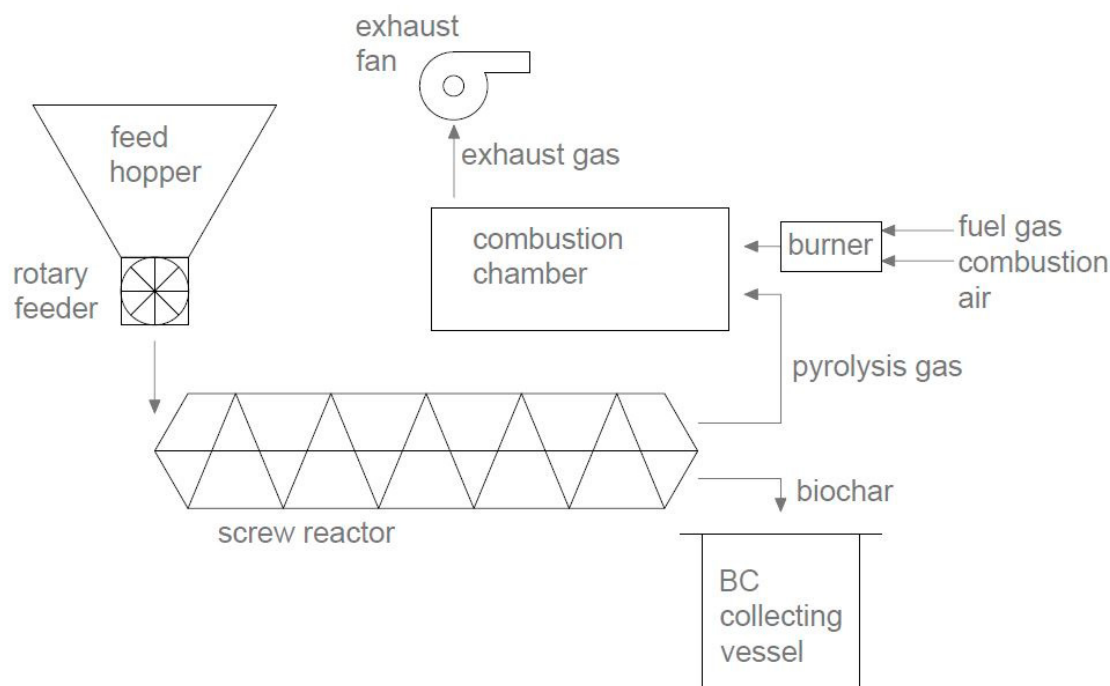


Figure 2. Schematic sketch of the screw reactor for the pyrolysis of sunflower husks (SFH).

2.2.4. Elemental Analysis of the Biochars

The produced BC and bio-oils were weighed in order to study the influence of process temperature and residence time on the mass balance.

Proximate analysis was carried out with the hazelnut shells (HNS) and the produced BC samples according to [17]. The weight proportions of the moisture, ash and volatiles were measured and the fixed carbon was determined by subtraction.

A “Leco-628 CHN3607, USA”-CHN-analyzer was used for the elemental analysis of the hazelnut shells and the BC samples. The weight proportions of C, H, N and S were determined and O content was calculated as difference by subtraction, including the ash content. These results were used for calculating O/C and H/C ratios in order to show their positions in a van-Krevelen diagram, where the stability of BC was assessed as described in [18]. In this diagram, the atomic ratios of hydrogen/carbon are plotted as a function of the oxygen/carbon atomic ratios. The van-Krevelen diagram is frequently used to show the evolution of biomass components during thermal processing. The European Biochar Certificate requires the compliance with specified ratios of $\text{O/C}_{\text{org}} (<0.4)$ and $\text{H/C}_{\text{org}} (<0.7)$ for quality biochar [19].

2.2.5. SOC as Carbon Sink in Austrian Soils

The 4 per mille objective [3] was used as a guideline to calculate the theoretically required C sequestration rate for the compensation of anthropogenic greenhouse gas emissions in Austria. A recent report by AGES [20] gave an overview of Austrian SOC contents and stocks which served as a basis for estimating potentials for C sequestration in Austrian soils. The highest potential was identified for degraded areas or areas with low SOC content [3]. Therefore, existing regional data were analyzed, supplemented by a few estimates for unreviewed areas (for further details see Table 3). The estimation of the SOC stock for “other” areas (non-agricultural, non-forestry areas) was based on the assumption that the sealed and urban areas have an estimated SOC stock of around 40 t ha^{-1} , that waters have

rather lower SOC stock considering that many of them have mineral material on the ground and the lion's share are alpine regions above 1800 m with an overall area of 1.11 Mha (Land Kärnten, 2019) (partly contained in unproductive area), which mostly consist of rocks or a very shallow top soil and therefore a very low SOC stock. Hence, an estimation of 10 t ha^{-1} has been chosen for "other". For the unproductive area of holding, a stock of 50 t SOC ha^{-1} is estimated since most of that area is fallow land which should have SOC stocks similar to crops (70 t ha^{-1}) and the rest are farm or country roads, etc., which are lower in SOC.

Since there are no data available for the SOC potentials of the different soil types, several assumptions were made in order to determine ideal sequestration rates. Based on studies of different countries on best management practices for C sequestration [3], the sequestration stock boundary to reach the 4 per mille goal was derived as $75\text{--}80 \text{ t C/ha}$ in the top 30 cm soil layer. Using this SOC stock goal (75 t C/ha in 30 cm), the sequestration potential of each soil type in Austria was calculated by the difference in SOC stock and goal.

2.2.6. Data Analysis

For the statistical evaluations and graphical presentation of the data, SigmaPlot 14.0 was used (Systat Software GmbH, DE-40699 Erkrath, Germany).

3. Results

3.1. Process Comparisons in Different Reactors

Figure 3 shows the mass balances of the fixed bed reactor and the rotary kiln as a function of temperature. In the fixed bed reactor, rising temperature clearly decreased the fraction of BC, while increasing the bio-oil fraction. This trend was very pronounced in the lower temperature part and continued with a lower impact at higher temperatures. Due to a variability in the water content of the input material (6–10%), the water fraction also varied in the mass balance. No distinct trends were detected in the behavior of the gas.

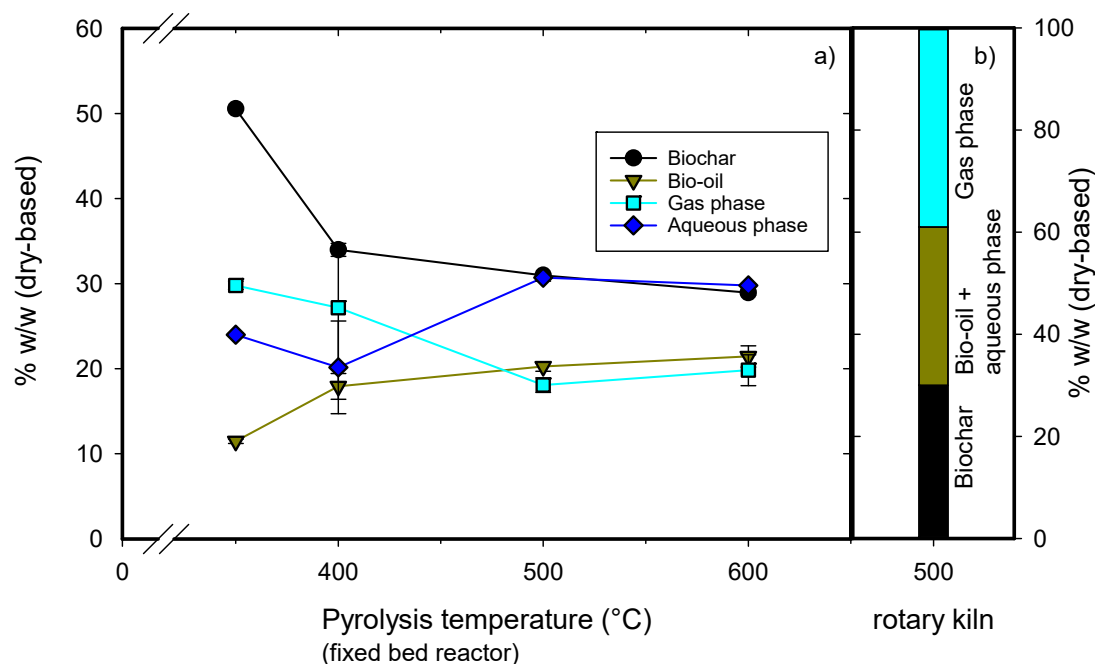


Figure 3. Effect of the process temperature on the mass fractions in (a) the fixed bed reactor and (b) the rotary kiln obtained from hazelnut shells (HNS).

The experiment in the rotary kiln showed similar behavior in the temperature dependency of the BC, but the gas fraction significantly differed from the fixed bed reactor, with a share of 31% in the rotary kiln and ~18% in the fixed bed reactor. Most likely, this was due to a higher retention time in the rotary kiln. The fraction bio-oil + water was distinctly smaller after the rotary kiln process (31% on input mass) than the product of the fixed bed reactor process (51%).

3.2. Ultimate and Proximate Analyses of Biochars

The elemental composition of the BC samples obtained from the HNS is presented in Table 1. While the C content increased with rising temperature, the H and O content decreased, thereby shifting the atomic ratios of the elements in a corresponding van-Krevelen diagram to the region of greater C stability (Figure 3). Due to the higher residence time in the rotary kiln, the decomposition progress of the hazelnut shells was more pronounced, and more O and H had volatilized, resulting in a higher C content.

Table 1. Ultimate analyses of the biochar samples in wt% (dry-based); O content was calculated by difference.

Input-Material	T in °C	C	H	N	S	O	Ash
HNS	350	69.0 ± 0.2	4.88 ± 0.03	0.52 ± 0.03	<1	23.4 ± 0.2	1.2 ± 0.1
HNS	400	76.6 ± 0.3	4.03 ± 0.02	0.43 ± 0.02	<1	16.6 ± 0.2	1.3 ± 0.1
HNS	500	80.2 ± 3.0	3.55 ± 0.23	0.53 ± 0.02	<1	13.2 ± 3.4	1.6 ± 0.6
HNS	600	81.5 ± 0.1	3.32 ± 0.03	0.52 ± 0.01	<1	12.1 ± 0.1	1.6 ± 0.1
SFH	450	68.6 ± 0.6	2.6 ± 0.4	3.4 ± 0.4	n.d.	7.9 ± 5.9	17.4 ± 6.4
SFH	600	71.1 ± 0.6	2.3 ± 0.4	3.4 ± 0.1	n.d.	12.0 ± 0.1	11.1 ± 0.1

Since higher process temperatures in the pyrolysis process usually cause a rise in the aerogenic reactions [21], an increase in fixed carbon and a corresponding decrease in volatiles with the rising pyrolysis temperatures were observed (Table 2). The higher retention time in the rotary kiln reactor allowed for longer reaction periods and therefore increased the devolatilization.

Table 2. Proximate analysis of the HNS-biochar (BC) samples in wt% (dry-based). Ash data are given in Table 1.

T in °C	Fixed C	Volatiles
350	45.4 ± 1.3	53.4 ± 1.3
400	63.4 ± 0.1	35.4 ± 0.1
500	70.3 ± 3.9	28.1 ± 4.5
600	73.5 ± 0.2	24.9 ± 0.3

The van-Krevelen diagram showed a clear trend of decreasing O/C and H/C ratios in the analyzed biochars with the rising pyrolysis temperature (Figure 4). There are several possibilities to estimate the stability of BC [18], among them, ultimate analysis and relating the fractions of O, H and C to one another are a low-cost and proven method. Spokas [14] suggested that BC with O/C ratios higher than 0.6 might have a stability of <100 years, O/C ratios between 0.2 and 0.6 indicate a stability for 100–1000 years and BC with O/C ratios <0.2 could have a half-life of >1000 years. The minimum requirements according to the guidelines of the European Biochar Certificate (EBC) are marked with the shortly dashed lines in Figure 4 at O/C = 0.4 and H/C = 0.7. This indicates that in the case of HNS, the minimum pyrolysis temperatures should be 400 °C if the BC is intended as soil amendment with the additional benefit of C sequestration. Since the BC samples produced at 350 °C clearly exceeded both minimum ratios and also the 400 °C samples still were close to those boundaries, it is suggested to use pyrolysis temperatures of 500 °C or higher in practice. Furthermore, the HNS-BC produced with the rotary kiln was characterized by even lower elemental ratios than those produced in the fixed bed

reactor (Figure 4), most likely because of the longer retention time. The SFH-BC samples also showed low ratios, positioning themselves inside both the desired areas. A shift towards lower elemental ratios was also found at longer retention times (30 instead of 10 min) and higher temperatures (600 instead of 450 °C), similar to the results of the HNS-BC (Figure 4).

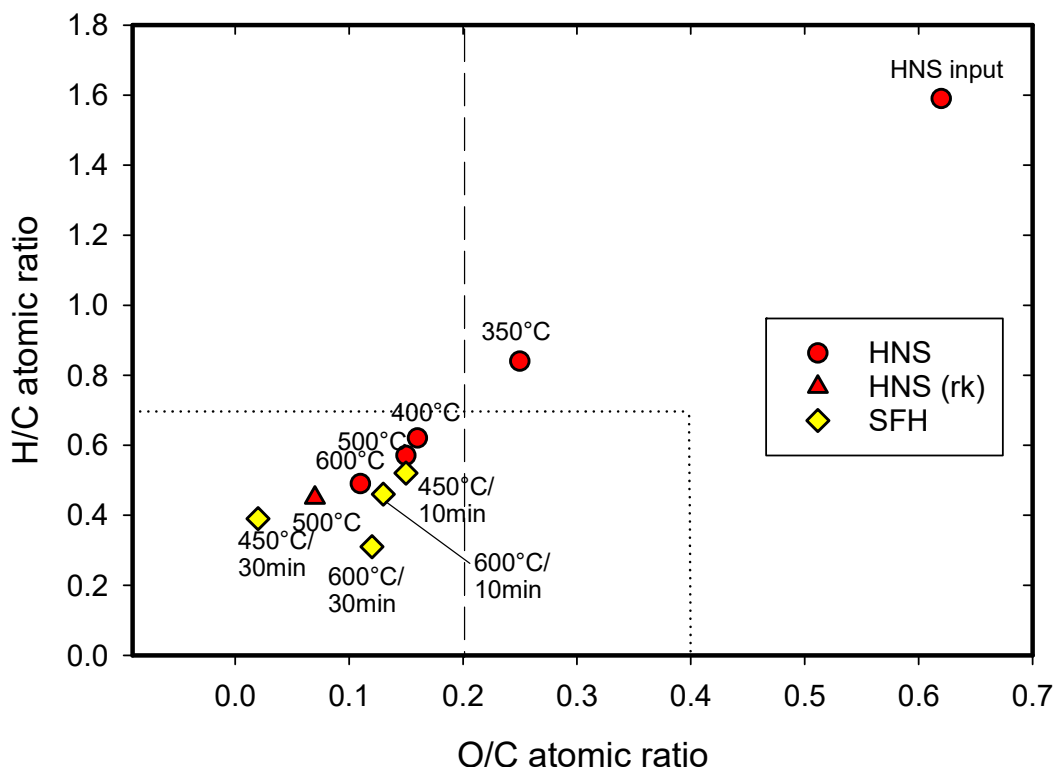


Figure 4. Effect of the process temperature on the elemental composition of HNS- (red symbols) and SFH-biochar (yellow diamonds) shown in the van-Krevelen diagram. The long dashed line shows an orientation line for the biochar stability at O/C = 0.2 according to [18] and the shortly dashed lines show the boundary area for quality biochar according to the European Biochar Certificate (EBC) [19]; rk ... rotary kiln, HNS ... hazelnut shells, SFH ... sunflower husks.

These results and the proximate analysis confirmed that higher pyrolysis temperatures and longer retention times were connected to higher C concentrations in the BC and to a more stable BC, confirming results reported in other studies [21,22]. The suitability of biochars produced from agricultural residues and at sufficiently high temperatures for long-term carbon sequestration was also confirmed by [23,24]. In these studies, higher temperatures reduced the O/C and H/C ratios and improved the stability of the biochars, even when different reactor types were used.

4. Discussion

The results obtained from the analyses of the tested biochar materials have shown that pyrolyzed hazelnut shells and sunflower husks are suitable amendments for long-term C sequestration in soil. Usually, pyrolysis reactors are operated at 500 °C or higher if the production of degradation-resistant biochars is pursued. Most commercial biochar reactors operate at temperatures of 500–600 °C if not run for other biochar application purposes, e.g., as sorbents for soil or water remediation [25].

Based on these results that biochars produced from easily available food crop processing residues are useful as soil amendments for carbon sequestration, the options for implementing a biochar strategy to achieve the “4 per 1000” objective was analyzed. For this purpose, a survey of soil organic carbon in Austrian soils and their potential as carbon sink was investigated with an eye on the use of compost and biochar as organic carbonaceous soil amendments. Table 3 shows the surface areas of different land use

forms in Austria, based on a report by Statistik Austria [26], the corresponding SOC stocks [20] and the calculated or estimated (**, ***) total SOC stocks. These data were used to calculate the total Austrian SOC stock (~631 Mt) in order to determine the necessary 4‰ increase overall by multiplication with 0.004 (~2.5 Mt), respectively 0.3 t C/ha annually. Considering that the agricultural area only accounts for ~32% of the total land area, this equals to about 0.9 t C/ha annually.

Table 3. Area and soil organic carbon (SOC) stocks of different Austrian land use forms. (*. calculated by difference of total Austrian land area and the other land use forms; **. estimated for “other” (see Section 2.2.5); ***. estimated for the unproductive area of holding (see Section 2.2.5)).

Land Use Form		Area in Mha	SOC Stock in t/ha (30 cm)	SOC Stock in Mt (30 cm)
agricultural area	permanent grassland	2.66	75.0	199.8
	crops, vineyards and orchards	1.26	72.6	91.4
		1.40	69.1	97.1
	crops	1.34	69.7	93.7
	<i>vineyards and orchards</i>	0.06	56.7	3.5
forestry area		3.41	106.0	361.2
unproductive area of holding		1.18	50 ***	59.1
other (urban and sealed area, surface waters, Alpine regions, etc)		1.13 *	10 **	11.3
Country area TOTAL		8.38	75.3	631.4
			Required annual increase (for 4‰)	2.53

Since permanent grasslands represent land use forms which are difficult for C sequestration via BC and compost because soil incorporation would be too disruptive and require a new grassland installation, the focus for the following calculations lies on crops, vineyards and orchards. The necessary 4‰ SOC increase on only those land use forms would equal to about ~1.8 t C/ha annually.

For reaching the suggested 75 Mt C stock, the sequestration potentials were determined by the difference in SOC goal and stock: for crop land, 7.1 Mt C (5.3 t/ha), and for vineyards, 1.1 Mt C (18.3 t/ha). This accounts for an SOC increase share of around 2.2 Mt C (1.6 t C/ha) for crops and 0.3 Mt (5.6 t/ha) annually for the 4 per mille objective. These values partially exceed the recommendation of the maximum compost rates in the Austrian compost directive [6] even though these application rates would have to be used for 100% of the mentioned area, which is not realistic. Hence, even higher application rates would be needed. Therefore, complementary measures that are also effective to raise SOC are in demand. In Austria, the so-called ÖPUL (Austrian Programme for Environmentally Responsible Agriculture) [27] promotes measures for minimum tillage practices like hardy soil cover greening for areas endangered for erosion, catch crops, direct seeding or the enhancement of biodiversity, which aim at environment-friendly extensive agriculture, also promoting and preserving the SOC.

Based on our experiments, we assume that BC produced from HNS at 600 °C may add around 800 kg C/t BC to the soil, additional to the beneficial side-effect of slowly releasing also 30–50 kg N/t BC, 10 kg P/t BC and 70 kg K/t BC, based on lignocellulosic BC [1] and demonstrated in the Results section. Thus, about 1.25 t of BC is needed for adding 1 t of C. Considering that around 3% will be mineralized quite fast from the labile C pool of BC [1], a factor of 1.3 is used for the C/BC ratio (1.3 t of BC for 1 t of C). With an actual price for commercial biochar of 600–800 EUR/t [28], the achievement of the 4 per mille objective based on BC only would cost EUR 2–2.5 B in total or 1400–1750 EUR/ha each year, which is quite expensive and far above the average marginal return per ha for common annual crops. Considering the external benefits for the climate, subsidies could be applied, but they would have to be very high to make such prices profitable. Therefore, scenarios with compost only and a mixture of BC with compost also have to be considered. However, it can be expected that biochar prices will decrease significantly with an increased development of the biochar market as well as the transition to residues as feedstock for the biochar production.

The total organic carbon content of various compost types typically ranges from 16 to 24% [29], so we assumed 20% as average: this means that 1 t of C corresponds to ~5 t of compost. It is important to consider that a significant share of the amended compost will be lost due to mineralization. The price

for compost in Austria is typically around 20 EUR/t. Therefore, if only compost amendment in crops, vineyards and orchards were used in order to reach the 4 per mille goal, ~ 9 t/ha or 12.6 Mt overall of compost, costing around EUR 250 M would be necessary. This corresponds to a price of about 180 EUR/ha. Even without taking any C losses, feedstock availability or economic considerations into account, a compost amendment of 9 t/ha would slightly exceed the limit for agricultural soils given by the Austrian compost directive [6]. These limitations show that a strategy based on compost addition only would not be sufficient. Compost apparently could contribute only a minor fraction for the achievement of the 4 per mille objective.

Deduced from typical BC application rates of 10–50 t/ha [30–32] and its relatively high price, 10 t/ha can be seen as a realistic goal for the future, if not applied annually. Even with the amendment of pure BC, less than 2.5 t/ha annually would be demanded for the 4 per mille objective. However, due to its recalcitrance, this goal could be reached through annual amendment. Roobroeck et al. [33] provided a model to design an adequate strategy. Considering that the availability of a compost and BC amendment in sufficient amounts for all Austrian crop, vineyard and orchard areas are unrealistic, the rates would have to be even higher to compensate for the not amended areas. Figure 5 shows the costs of scenarios with amendment on all those soils with different BC/compost ratios, in order to give an orientation for further developments of agricultural soil management. These estimates show that a mere compost strategy is not possible and requires the addition of a certain fraction of BC to achieve enough carbon density of the amendment. This, however, would cause the price of the amendment per ha to soar, decreasing the chances of implementations for economic reasons. Therefore, the achievement of the “4 per 1000” objective with a mixture of compost and biochar is possible but the costs will require that also other soil management measures to increase soil carbon will be indispensable.

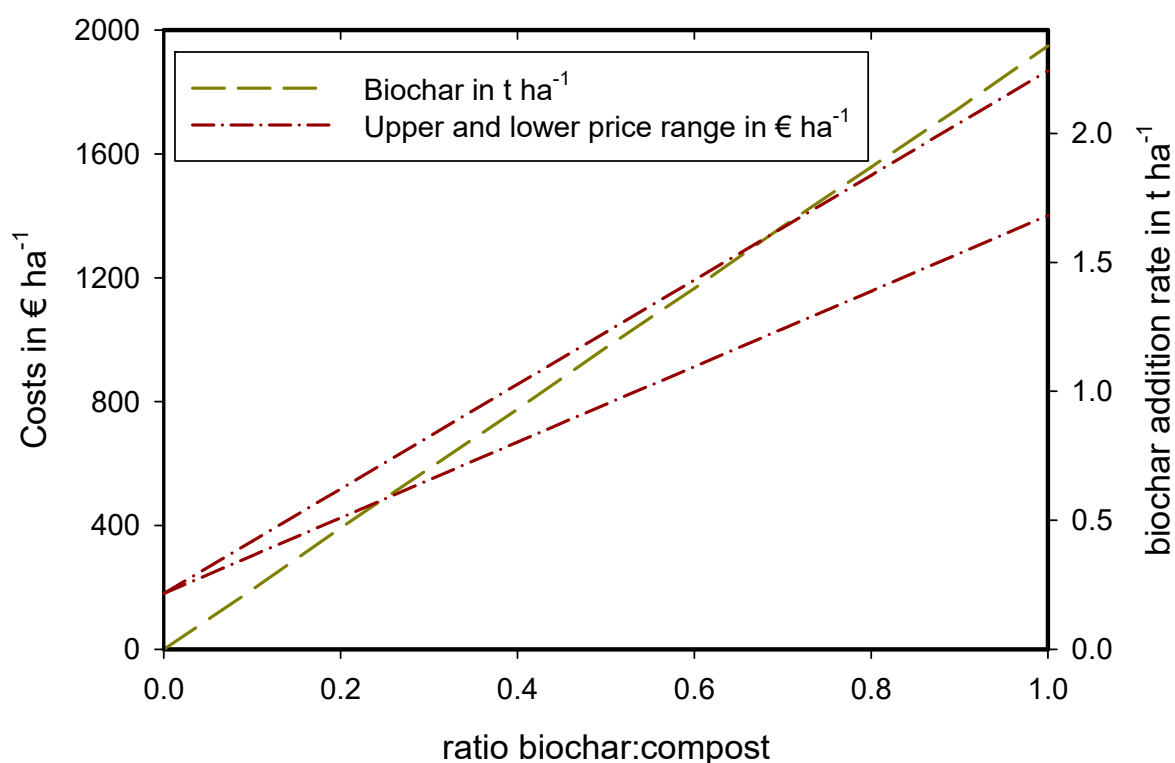


Figure 5. Average costs for C sequestration according to the 4 per mille objective on all Austrian crop areas, vineyards and orchards for BC-compost ratios from 0/1 to 1/0.

5. Conclusions

Rising pyrolysis temperatures decreased the yield of biochar and increased its C content in different types of reactors. The selection of feedstock and reactor type played a minor role because all biochars produced at pyrolysis temperatures of 500 °C or more would contribute significantly to the long-term SOC enrichment. It was shown that the 4 per mille objective is a good guideline for C sequestration in Austria but production prices for amendments and mostly high levels of C in the soils diminish the sequestration potential in arable land, vineyards and orchards. The price differences between compost and biochar and their widely different carbon residence times in soil will require a deliberate compromise for an economically feasible application rate. Additional alternative C sequestration measures, negative carbon emissions and a comprehensive climate farming strategy will be needed if the 4 per mille objective shall support the mitigation of the current accumulation of greenhouse gases in the atmosphere.

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