Biochar:
Production and testing in small-scale use

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Contents

1 Introduction

Agricultural practices and methods have always been evolving, and did so at even faster rates over the last decades. The development of new and improved technologies, such as agricultural machinery, pesticides or fertilizers, all have the same motivation: The goal of producing more crop in a more efficient way, requiring less surface and work for a better harvest. Especially in a context of climate change, fast population growth and almost 1 billion people suffering from undernourishment, the need for improvement is tremendous (FAO (2019)). However, this development has often focused too narrowly on the optimization of the production, and has considered insufficiently other aspects, such as social or environmental ones. Resulting environmental problems often became visible a while after the implementation of a new agricultural practice, and it took even longer to understand the link between the problem and its source.

Today, many issues related to agricultural activities are known, and measures to reduce the impact and improve the health of the environment are taken. Nevertheless, the problems are far from being solved and the need for more *sustainable* methods ensuring a sufficient productivity has become extremely important.

Fertilization is one of today's main sources of environmental problems related to agriculture. Starting with the Haber-Bosch process (Fixation of atmospheric nitrogen into Ammonia) in the early 20th century, industrial methods to produce synthetic fertilizers started to replace the traditionally used natural methods (Russel & Williams (1977)). As a part of the *Green Revolution* in the mid-20th century, fertilization rates increased drastically, leading to the emergence of environmental issues (Lu et al. (2017)). Lake eutrophication is probably the best-known example, as it peaked in 1970-1980 in Switzerland due to high phosphorous loads entering the environment, with an important fraction coming from agriculture (OFEV (2020)). As the phosphorous loads have been strongly reduced since, the eutrophication has decreased in many lakes. However, other issues related to fertilization are still of major concern, such as groundwater pollution, sea eutrophication or greenhouse gas emissions.

On the contrary, biochar used as a fertilizer is known to have many environmental benefits. According to Hussain et al. (2017), these include global warming mitigation, restoration of degraded land, removal of organic compounds in water, reduction of greenhouse gases, improvement of the soil's water retention capacity and overall fertilization of the soil. Furthermore, biochar is thought not to have the impact of over-fertilization, as it releases the nutrients at a slow and steady rate, while industrial fertilizers add big amounts of nutrients at once. Hence, in the case of biochar fertilization, more of the added nutrients can be absorbed by the plants, and less is lost through leaching into the environment.

With that context kept in mind, this project aims to present biochar as a biological fertilizer that seems to have much less environmental impact and could hence potentially replace industrial fertilizers. For this, a simple way of producing biochar is presented in chapter 2, and its potential to ensure a sufficient productivity is tested in chapter 3.

2 Part I: The biochar stove

2.1 Physical-chemical process of organic matter pyrolysis

Biochar is the solid product of the pyrolysis of organic matter. This is the process of thermal decomposition of organic matter at relatively low temperature (350 to 900 °C) in absence of oxygen (Godlewska et al. (2017)). In this pyrolysis reaction, the initial biomass is transformed into gaseous, liquid and solid compounds. The proportion between the different products is strongly determined by operation parameters, such as temperature or residence time. In fact, slow pyrolysis at low temperatures seems to produce a much higher solid fraction (up to 80% of the total mixture) than faster and hotter processes (Bridgwater (2015)). Furthermore, methods such as gasification or fast pyrolysis require more advanced technology than what is in the scope of this project. Both these arguments lead to the obvious choice of a slow pyrolysis stove for this project, as it can be achieved with rather simple methods.

Chemically, the pyrolysis of organic matter is not defined by a simple reaction mechanism, but rather by an entire set of combined processes. This heterogeneous mode of chemical transformation has several reasons. First, biomass in itself is a complex mixture of compounds with different chemical properties, that all react in different ways. Besides, the water content varies between individual compounds of a biomass mixture, which might further influence their reactive behavior. Second, especially in simple pyrolysis stoves, the heat addition and (low) oxygen concentration is not homogeneous throughout the stove and over the operation time. As explained before, as the process conditions affect strongly the outcome, this has an important impact on the biomass transformation.

Several models for single-compound pyrolysis have been established, that aim to predict the different products and their proportions after the process (Di Blasi (2008)). On the one hand, such models require a very good knowledge of the reaction mechanisms related to that specific compound, and on the other hand, the kinetics of the individual reactions need to be studies in order to predict their importance at given process conditions. Figure 1 presents such a model for the case of cellulose pyrolysis. The complexity of a single-compound model is already very high, indicating that the process of a compound mixture is very hard to understand entirely and even harder to model. Hence, most of the studies about biomass pyrolysis aim to describe the process empirically rather than analytically.

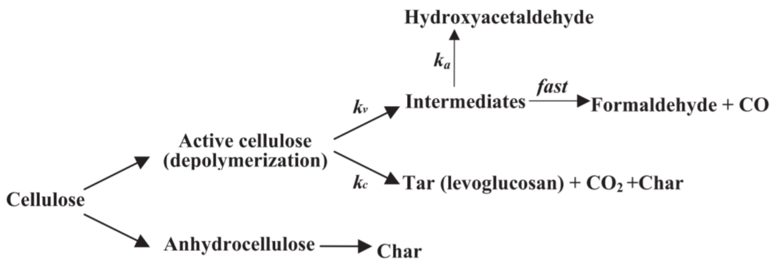

Figure 1: Pyrolysis model developped by Banyasz et al. (2001) for cellulose, illustrating the complexity of a single-compound pyrolysis. The kinetic rates (k_i) depend on the process conditions and require each to be studied separately.

A fundamental understanding of the process is required when a biochar stove has to be optimized for a given substrate. As this is not the case for this project, qualitative descriptions of the relationship between the products and the process parameters are sufficient, and have led to the choice of a slow pyrolysis process.

2.2 Stove construction

The biochar stove built in this project follows the concept developed by Kelpie Wilson, a teacher at an alternative school in Oregon, US (Wilson (2010)). The original "dome school biochar stove" is made from empty food cans and is very small, designed to be run with wood pellets. The concept of this stove was already scaled up by the use of old oil barrels, to produce biochar for a permaculture project

(Bradley (2013)). As all reports found described it as a well working low-tech concept of a biochar stove, it was chosen for this project.

To achieve a reasonable amount of biochar, an intermediate size between the food cans and the oil barrels needed to be found: Empty color cans from SOCOL SA, with a volume of 20 and 12 liter finally were a good fit.

Figure 2: The biochar stove produced: two layers of cans with an aeration system from the bottom and holes for pyrolysis gases to escape on the top of the inner can. Finally, the lid with a hole in the center aims to maximize the heat in the stove while ensuring a sufficient flow of oxygen for the fire.

Having the two cans, the construction is rather easy. First, the inner can's bottom side is perforated until it's entirely covered with holes. Additionally, large triangles are cut in the sidewall near the bottom of the outer can. These two operations ensure a sufficient but minimal bottom aeration of the stove to keep the fire burning, while the necessary oxygen-poor conditions are maintained. Second, triangles are cut in the upper sidewalls of the inner can, which ensure an escape pathway for the pyrolysis gases produced inside the stove. Finally, the last step consists in cutting a hole in the lid to ensure an equilibrium between a sufficient air flow and a good insulation.

2.3 Biochar production

Several substrates were used to produce the biochar. While the initial goal was to use mainly biowaste (kitchen waste, chicken manure) and only some wood as a fuel, it turned out that quite an important proportion of wood is required to make the pyrolysis happen. In fact, especially the kitchen waste is very moist and burns very badly. As table 1 shows, wood made up about two thirds of the wet mass of the total substrate used.

It is possible that a more sophisticated and professional biochar stove would succeed better in the pyrolysis of fresh biowaste, as higher temperatures are reached. In fact, the reason for the bad pyrolysis behavior of the biowaste could be an insufficient operation temperature. Monitoring the temperature in the stove during its use could confirm this hypothesis.

Substrate used	**Wet weight [kg]**	**Moisture [% mass]**	**Dry weight [kg]**	**Proportion [% wet mass]**
Kitchen waste, chicken manure	4.2	64 [1]	1.5	37.5
Wood	7	15	6	62.5
Total	**11.2**	30	**7.5**	
Biochar produced	**6.4**	<5	**6.1**	

Table 1: Total mass used and produced during the production of biochar ([1]Andersen et al. (2011)). The moisture content of the final product is assumed to be almost zero as it was heated much above the boiling point of water.

The stove was filled up several times to produce a sufficient amount of biochar. Figure 3 illustrates how the stove is used. To prevent the biochar from a further oxidation after the process, it is put into a bucket of water. Without doing so, it would be possible that it continues to burn, which is not only dangerous for the place where it's stored, but it might also turn the gained biochar into ash and make it useless for further use.

Figure 3: The working principle of the stove: fresh biomass is filled in the bottom of the stove, wood is added on top of it, lit on, and once it burns well, the lid is put on.

2.3.1 Mass balance comparison

To compare the use of biochar to that of compost, the total mass flow needs to be considered. That means, if a cultivation with biochar addition delivered better harvests than one with compost addition, but much more biowaste and energy was needed to produce that biochar, its economic advantage might be debatable. It would be difficult to make consistent conclusions in that case. As a prevention for such an outcome, the same amount of initial substrate, before transformation into compost and biochar, is used for the setup of the experiments. How this was done will be explained more in detail in section 3.1.

Table 1 shows a reduction in wet mass of about 43% during the process of biochar production. While the substrate mixture used contained about 30% moisture (Andersen et al. (2011)), the final product is assumed to be almost dry, as it was heated above the boiling point of water for at least 30 minutes.

In comparison, the compost is assumed to have a wet-mass reduction of about 56% (Andersen et al. (2011)). Hence, the same initial mass of 11.2 kg resulted in approximately 5 kg of compost (see table 2). This amount was added to the compost experiment.

	Biochar	Compost
Initial substrate mass [kg]	11.2	11.2
Mass loss [% wet]	43	56 [1]
Final wet mass [kg]	6.4	5
Moisture content [%]	<5	67 [1]
Final dry mass [kg]	6.1	1.65

Table 2: Calculation of the required amount of compost considering the same initial wet mass, to ensure a comparable experimental setup. ([1] Andersen et al. (2011))

The mass balance of the biochar production suggests that the process is slightly more efficient in terms of fertilizer produced per biomass used, when compared to the composting process. However, in chapter 3, the efficiency of both fertilizers in agricultural and horticultural applications will be discussed.

3 Part II: Biochar quality test

Having a way to produce biochar in a simple manner was the first goal of this project. The second aim is to use the product from the previous section and to study its potential in vegetable gardening. This is done in a comparative way, notably by cultivating radish and spinach in three different soil mixtures while ensuring the other environmental conditions are the same. Hence, the biochar-containing soil is compared to a compost-containing one and to one without nutrient addition.

Initially, several growth parameters were to be measured on the vegetables. Due to the Coronavirus outbreak, the measurement instruments were not available and the study had to be modified. It is for that reason that the final result is a timelapse video of the plant growth and the comparison of the vegetable harvest on a weight base. Nevertheless, these adapted methods were more than satisfactory to get some interesting results and to draw a few conclusions.

3.1 Experimental setup

Three plant pots were used to conduct this experiment. The first one ("Control") contained only a sandy soil, while the second ("Compost") and the third one ("Biochar") contained the same soil but were enriched with compost or biochar, respectively.

As plant growth is influenced by various parameters, it is essential to ensure very similar growth conditions to all experiments, and to only modify the parameter that is to be studied. Hence, the central working principles of this study are presented here.

- The initial soil mixture (before the nutrient additions), the exposure to sunlight and the irrigation were the same for the three experiments.
- The seeds of both the radish and spinach were placed in exactly the same line-up, as can be seen in figure 4.
- The timing of the sowing and the harvest is the same for the three experiments.
- The experiment was undertaken in isolated garden pots rather than in the open soil to ensure the same "history" of the substrate the plants grow in.

As biochar is a slow-releasing fertilizer, its benefits are often not seen in the first cropping season (Major (2009)). Having a very nutrient-poor soil will increase the impact of a biochar addition and make its effect become visible faster. Therefore, an extremely poor soil mixture was created, containing more than 50% sandy sediments from Lake Geneva. These sediments were obtained from *Sagrave SA*, a sand and gravel company that excavates sediments from Lake Geneva, which are then used mainly

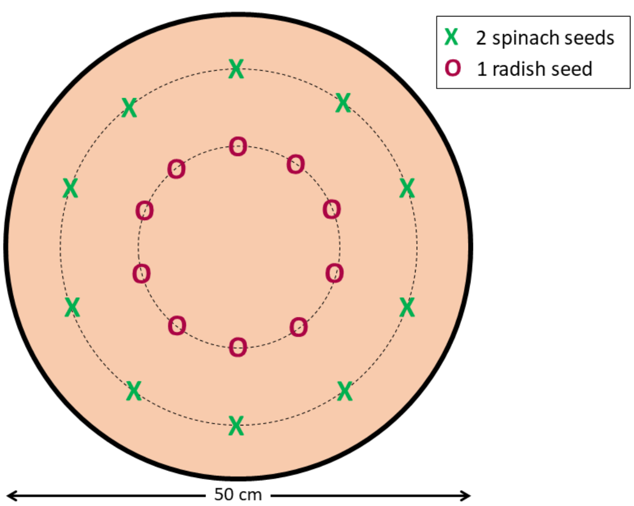

Figure 4: The line-up of the seeds is the same in each pot. On the inner ring, 10 seeds of radish were planted in regular distances, while on the outer ring, 10 times two seeds of spinach were planted. This setup corresponds approximately to the standard way these vegetables are cultivated, even if it is usually done in straight lines rather than circles.

for concrete production. As these sediments contain extremely little nutrients and organic matter, they are an excellent resource to produce the low-quality soil required for this project.
To ensure the minimal requirements in nutrients, some normal soil was added to the mixture, which was obtained from a construction site in St-Sulpice. The final composition of the soil is described in table 3.

	1 - Control		2 - Compost		3 - Biochar	
Lake Geneva sand	32 kg	42.7 %	30 kg	40 %	30 kg	39.3 %
Soil from a construction site	43 kg	57.3 %	40 kg	53.3 %	40 kg	52.4 %
Fertilizer (compost or biochar)	-	0 %	5 kg	6.7 %	6.4 kg	8.3 %
Total	75 kg		75 kg		76.4 kg	

Table 3: The three mixtures of soil. Having all the same basis of soil and sand, mixtures 2 and 3 contain in addition some fertilizer.

3.2 Results and discussion

The sowing was conducted on the 4th of March 2020. The radish harvest happened on the 17th of April (after 44 days) and the spinach was harvested on the 4th of May (after 61 days). The time of harvest was chosen when the first of the three pots was ready, to allow the comparison of the outcome of the same growth duration. Hence, the results indicate a stronger or weaker growth *in the same time period*; possibly, the pots with smaller harvests would lead to the same result as the others, but require more time to get there. However, having a good harvest more rapidly is favorable in the garden, as it allows to grow other crops after the harvest.

Figure 5: Result from the radish harvest. The compost and biochar (2 and 3 respectively) experiments delivered bigger (heavier) radish than the control one (1), even though two radish in the compost mixture grew very poorly.

3.2.1 Harvest comparison

Radish

In each pot 10 seeds of radish have been planted. At the moment of harvest, the majority of the plants in the compost and biochar mixture were ready, while the control experiment clearly lagged behind, as can be seen in figure 5.
Table 4 shows the comparison between the different experiments. As the germination efficiency of the seeds is not in the focus of this project, and no explicit statement about the soil's influence on the germination could be made, the number of radish and the total weight have less significance than the average weight of one radish. Hence, this is considered the main measurement parameter for the comparison.

The data shows very clearly that the soil without fertilization leads to less favorable growth conditions, and the radish develop much less. The mean weight of these radish is only about 6.5 g, while the fertilized ones are both around 10 g, the biochar even slightly above.

	1 - Control	2 - Compost	3 - Biochar
Number of radish	8	9	9
With leafs			
Total weight [g]	76	133	131
Mean weight per radish [g]	9.50	14.78	14.56
Without leafs (edible part)			
Total weight [g]	52	89	94
Mean weight per radish [g]	6.50	9.89	10.44
Minimum weight [g]	2	6	<1
Maximum weight [g]	8	17	17

Table 4: Result of the radish harvest. The control experiment resulted in a much smaller harvest, while the compost and biochar experiments delivered similar results.

Interestingly, the compost experiment led to a higher fraction of leaf weight. This could be due to the competition for light, as much more undesired weeds grew in this pot, as will be discussed more in section 3.2.2. Furthermore, two radish in the compost experiment germinated but didn't develop well. From the available data it is not possible to clearly see if this was due to the soil conditions, due to the seed quality or for any other reason. However, they lower the per-radish weight grown in compost, and make the radish of this experiment look smaller than the biochar ones. Hence, the significance of this difference is not important enough to clearly say that the radish grew better in the biochar than the compost. An honest result is probably to say, that biochar and compost both increase the soil quality and growth conditions for radish when compared to a nutrient-poor soil, but no significant difference between the two could be observed.

Spinach

20 seeds of spinach were planted in each pot. As mentioned in the radish harvest, the germination efficiency and hence the total weight are not the most significant results from this study, but mainly the per-plant and per-leaf analysis.

	1 - Control	2 - Compost	3 - Biochar
Number of grown plants	12	11	14
Total number of leafs	95	102	127
Mean number of leafs per plant	7.92	9.27	9.07
Total weight of leafs [g]	33	102	92
Mean weight per plant [g]	2.75	9.27	6.57
Mean weight per leaf [g]	0.35	1	0.72

Table 5: The results from the spinach harvest. The compost mixture seems to lead to the growth of bigger spinach leafs, followed by the biochar mixture and finally, far behind, the control soil.

While the radish harvest delivered similar results for the compost and biochar experiments, the spinach seems to grow better in the compost experiment, as illustrates table 5. At a first glance, the total leaf number of the biochar experiment seems to indicate a better harvest in this soil. However, the leafs grown in the compost mixture are considerably larger and heavier, making the entire spinach plant heavier than in the other two experiments. Nevertheless, the control experiment is again far behind the two others, with very small leafs and an unsatisfying harvest.

Figure 6: Result of the spinach harvest. The largest leafs grew in the compost soil (center), followed by the biochar soil (right) and finally the control soil (left).

3.2.2 Other observed differences

Not only the final harvest has to be considered as a quality of the soil, but also the work that was required to grow the crop. In particular, home gardening is usually not a full-time activity but rather a weekend hobby, meaning that the efforts made are irregular in time and not always as complete as they need to be. Therefore, the observation made in the compost experiment might influence a homegardener's choice of what fertilizer he wants to use: A lot of undesired weeds grew in the compost experiment, much more than in the two other pots. In fact, the used compost must have contained a lot of seeds that germinated when they were put in favorable conditions. Hence, regular efforts would be required to eliminate those weeds and to eliminate competition for nutrients, water and light. This is illustrated in figure 7.

Figure 7: Much more growth of undesired plants was observed in the compost experiment (left) than in the two others (Biochar: right). Hence, vegetable cultivation using compost as a fertilizer might require more work than cultivation with biochar.

Furthermore, the capacity to retain water was considerably better in the fertilized pots. The control soil was always very quickly dried-out at the surface, and irrigation was required almost daily. This suggests that elevated concentrations in nutrients and organic matter lead to a better water retention capacity of the soil, which is confirmed by other studies (e.g. Hussain et al. (2017)). Hence, the risk of crop failure due to insufficient water availability is strongly reduced in the compost and biochar mixture, and less irrigation is required to ensure a good water availability. Finally, this leads to a more economic cultivation, as less work and water is needed to irrigate the plants.

4 Conclusion

In the first section of this project, a biochar stove was built, that could be used in small-scale vegetable cultivation to produce a natural fertilizer. The working concept of the *Dome school biochar stove* was used here, which turned out to work fine, but leaves space for improvement.

First, the working temperature was around the minimal requirement for pyrolysis to occur. This had the consequence that only the very dry biomass was transformed successfully into biochar, and the more moist fraction didn't transform well or took very long to get there. Hence, a lot of fuel (wood) was required for the operation. A better insulation of the stove walls or an increased heat exchange between the fuel combustion zone and the biomass pyrolysis zone are two potential improvements that could solve this problem.

Second, the conditions inside the stove were not entirely anoxic, as some oxygen is required in the burning process. As a consequence, full pyrolysis cannot be achieved, as burning and pyrolysis happen simultaneously - If the fire is not quenched at the right moment, it burns slowly until only ash is left, and the biochar is entirely lost. A better solution would be to separate spatially the burning and pyrolysis processes. However, this would make the heat transfer from the burning zone to the pyrolysis zone less efficient, and a proper working temperature might not be achieved.

Nevertheless, as a simple solution the built stove seems to work well, and the produced biochar was satisfying.

The second part of the project aimed to test the fertilization performance of the produced biochar in the cultivation of radish and spinach, in comparison of no fertilization and compost fertilization. As presented in section 3.2.1, the biochar fertilization seemed to work successfully for both vegetables cultivated, as much better harvests were achieved than in the experiment without fertilization. However, it did not turn out to be a better solution than compost fertilization, as about an equal harvest was observed for the radish plants, and a slightly smaller harvest was achieved for the spinach plants. Hence, the conclusion drawn from this study is that biochar addition results in considerable improvement of soil fertility without being the outstanding solution.

However, the significance of this study's result is debatable. On the one hand, only one experiment per studied case was conducted, mainly due to logistical reasons, as neither the means nor the space was available to have another set of three pots weighting about 80 kg each. Hence, the randomness of the results is quite large, as error detection is very difficult.

On the other hand, due to the situation related to the Covid-19 pandemic, the required measurement devices were not available, which reduced the study's result to a harvest comparison. As biochar is known to have much more effects than just improving soil fertility (e.g. promote ion exchange, improve water retention, increase microbial activity etc.), it does not make sense to compare this solution only on its capacity of crop improvement. Other parameters, such as soil moisture, would help to get a more complete picture of the comparison between a compost and a biochar fertilization.

Finally, as explained in chapter 3.1, biochar is a slow-releasing fertilizer, that improves long-term soil fertility and overall health. Hence, an experiment of the first cropping season might deliver much different results than an experiment done during the growth of the second or third crops.

In conclusion, this study tested one aspect of biochar fertilization, but has left out several other aspects that are in fact crucial when talking about biochar. If biochar is to be tested as a powerful and sustainable tool for agriculture, a more detailed experiment over a much longer trial period needs to be carried out.

Nevertheless, its short-term fertilization capacity was tested successfully, proving that it is possible to produce biochar in simple ways and that it is an interesting alternative to other fertilization techniques.

4.1 Future scope - Project continuation

This project has a great potential to be continued by another student. Having a similar experiment carried out over the next cropping seasons would show the long-term effect of a biochar fertilization.

For this, the used pots with the different soil mixtures will be stored (probably at the *Ferme de Bassenges*) and made available for any further experimental use. In fact, several questions would be very interesting to be studied: What would be the result of the same experiment when tested on other crops, especially crops of other growth seasons? Do some plants prefer biochar fertilization, while others prefer an addition of compost? How does the moisture content evolve in the different pots, does biochar fertilization reduce the risk of drought-related stress?

For sure, several other continuation possibilities related to this project could be found. The "Guide to Conducting Biochar Trials" (Major (2009)) of the International Biochar Initiative suggests many study topics related to biochar and presents model frameworks, experimental setups and other considerations to be taken when studying these topics. Following this guide facilitates the comparison with other studies, as it aims to standardize the methods. Hence, the experimental setup was designed in accordance to this document, and any further study is encouraged to do so as well.

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