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Assessing the Use of Food Waste Biochar as a Biodynamic Plant Fertilizer

Rachel Mazac
Environmental Studies & Biology
Hamline University
1536 Hewitt Avenue
St. Paul, Minnesota 55104 USA

Faculty Advisor: Dr. Michael Farris

Abstract

Biochar is a charcoal-like substance produced from plant material such as food waste. Converting food waste into a useful product would mitigate environmental damage through reduced landfill inputs, reduced greenhouse gas production, and increased benefits to soils. This study asked (1) if biochar improved plant growth and (2) if the effects of biochar varied among different samples of mixed food waste (batches) and between different biochar preparation times (treatments). Four independent batches of biochar were prepared with assorted, uncooked food waste collected from a university dining facility. Each batch was dried, then placed in a covered ceramic pot at 260℃ for 3 or 6 hours under low oxygen (pyrolysis). Tomato plants (*Solanum lycopersicum*) were grown in soils with the eight batch-treatment biochar combinations or with no biochar (controls). Averaging over batches, the 3 and 6 hour treatments germinated significantly later than controls. Aboveground dry mass at 30 days did not differ significantly among the three treatments. Mean height growth rates (mm/day) were significantly higher in 3 and 6 hour treatments than in controls. Considering only biochar-treated plants, there was a significant interaction between pyrolysis time and batch for both germination time and height growth rate. Some batches germinated earlier when the biochar pyrolyzed for 3 hours was added, other batches when six-hour biochar was added. Plants emerging later had higher growth rates, leading to no significant difference in size at 30 days. Both pyrolysis time and food waste source material had varying effects on plant growth. While biochar had no effect on mean dry mass at 30 days, complex effects on germination time and growth rate suggest that growing plants to maturity may lead to differences in plant size. Future studies should investigate effects of different food waste types on plant growth and assess nutrient content of source material.

Keywords: Biochar, Food Waste, Climate Change Mitigation

1. Introduction

Biochar is an anthropogenic charcoal soil amendment that has the potential to address environmental problems such as soil degradation, food insecurity, water pollution from agrichemical sources, and even climate change. It has been suggested that stable carbon structures in biochar can even be sequestered in the soil for thousands of years[14].

Biochar, a biomass-derived black carbon, is similar to common charcoal. It is distinguished from charcoal by its use for environmental application and as a soil amendment to improve fertility and increase carbon sequestration[2]. Burning the biomass in a limited amount of oxygen turns it into char. This thermal degradation process of organic materials in the absence of air is called pyrolysis[9]. The biochar product can then be used to improve soil conditions, facilitate infiltration of pervading groundwater, and for carbon storage[16]. The most traditional feedstock for biochar is any woody biomass consisting primarily of cellulose, hemicelluloses, and lignin[16].

This study examined the use of food waste as the feedstock for biochar. Previous studies have not investigated the use of mixed food waste from a market or family kitchen as feedstock for biochar, and have not assessed the use of this biochar as a fertilizer for comestible plant growth. Chen and Chen[3] dried orange peels as feedstock for biochar using a laboratory oven to pyrolyze the food waste. In contrast, this study used mixed food waste obtained from university dining services pyrolyzed at conventional home oven temperatures. This "in-home" method was studied because a more accessible method would allow for the production of biochar on a small scale. Although industrial methods of mass producing biochar are possible and may be beneficial, production on a smaller scale or in developing countries would meet the demand for high-quality, economically-feasible fertilizer. Since food waste will never be completely eliminated, converting it to a useful product would both reduce environmental damage and provide a profitable use for waste items.

A UN Food and Agriculture Organization[5] report found the cumulative effect of food waste has significant impact on biodiversity, land and water use, and especially global climate change. Global urban food waste is predicted to increase up to 44% by 2025[1]. Hall et al.[7] found that food waste has already increased by approximately 50% since 1974. On an agricultural scale, 1.3 billion metric tons of food is disposed of each year with an annual economic impact of $750 billion[5]. This translates into more than 1400 calories per person per day, or 150 trillion calories per year going into landfills[7]. Landfill gases are a major source of anthropogenic methane emissions, due in large part to food waste. For every ton of food waste put into landfills, 125 cubic meters of greenhouse gas is emitted[8]. Of this, 60-65% is methane and 35-40% is carbon dioxide. Landfills in countries with a higher gross domestic product are responsible for 30-37% of total anthropogenic methane emissions in the world[19].

Alternative methods for the efficient and effective use of food waste are essential to mitigate future impacts on the biosphere. The goal of this study was to examine a productive use for food waste which could limit the amount added to landfills, and therefore limit the production of greenhouse gasses. These methods could provide families or small businesses with a means of upcycling their food waste into a useful and potentially profitable product.

The specific questions this study addressed were: (1) can effective biochar fertilizer be made from food waste? and (2) does the effect of biochar vary among batches of food waste or pyrolysis time?

Biochar was produced from food waste and then assessed for how effective it was as a fertilizer via a tomato (*Solanum lycopersicum*) growth assay. Germination day was recorded and growth measurements taken of the plants. Growth measurements included plant height at each day of data collection in millimeters of growth per day, and final aboveground dry mass in grams. The individual batches and separate pyrolysis times were also assessed in the same growth assay and compared to each other.

It was predicted that biochar would not have an effect on germination, as it is affected mainly by moisture, soil oxygen amount, and temperature[4]. These growth conditions were held constant between the control and biochar plants, so no effect of biochar on germination was expected. In the other growth measurements, it was expected that biochar amended plants would surpass the control plants. If biochar is an effective fertilizer, it should increase plant height, leaf canopy diameter, and leaf number, as well as increase the final aboveground dry mass when compared to the control plants. Growth rates of the biochar plants was also expected to be surpass that of the control plants.

2. Materials and Methods

The methods of Chen and Chen[3] were used as a basis for this study. Uncooked and unprocessed mixed food waste was collected by hand from the Hamline University dining facility kitchen. Food waste was chosen from kitchen food preparation scraps. No special consideration was taken in gathering the material for each of the four collected volumes of food waste, here called batches. Only the most available food waste was selected in the bin at the time of collection. Each batch was collected independent of the others. Processed or cooked food waste was not obtained; these foods were avoided to eliminate the addition of other substances (i.e. salt, oils, etc.) to the soil. Food waste components of each batch were recorded in order of decreasing abundance (Table 1).

Table 1. Composition of each batch, listed from most abundant to least abundant in the source food waste.

Batch #	Composition
1	Cauliflower stems, pineapple rinds and leaf tops, potato peels, egg shells, banana peels, celery stalks
2	Watermelon rinds, corn husks, egg shells, banana peels
3	Potato peels, pineapple cores, cantaloupe rinds, carrot greens, capsicum stems, grape vines
4	Carrots, celery stalks

Enough food waste was collected for 0.5 L of biochar per batch in order to obtain the required mixing rate of 5% by mass biochar in the soil[3]. Based on preliminary studies, a 2:1 fresh food waste to pyrolyzed biochar product ratio was expected, and around two liters of food waste was collected for each batch to ensure the sufficient amounts of biochar. The food waste was processed using the same methods for each batch, differing only in pyrolysis length. Each batch of food waste was hand-chopped into pieces smaller than approximately three centimeters. This chopped food waste was air dried in a greenhouse for two days. Each batch was set in trays and covered with a fine mesh to prevent insects from reaching the drying food waste.

The batches were oven dried overnight for 12 hours in a Fisher Scientific Isotemp 725g Laboratory Oven at 75℃. The oven-dry mass and volume was recorded for each batch. For pyrolysis, the entire batch was put in a glass-lidded, Corning Ware French White Round 2.3 L ceramic casserole dish and cooked at 260℃ in the above mentioned laboratory oven. Half of the volume was removed after three hours while the other half was left in the oven to pyrolyze for six hours. Four different batches of biochar were made using these methods; each was separated at the pyrolysis stage into three-hour and six-hour subdivisions. Pyrolyzed biochar was ground in an Osterizer Imperial Cycle Blend Pulse-Matic blender on high for approximately 15 seconds per batch until it became a fine powder.

Plants were grown in nine cm square pots in a greenhouse with daily watering on a timer for 30 days. Two hundred and four tomato plants (*Solanum lycopersicum*) were grown in low-nutrient Pro-Mix All Purpose Growing Mix. The seeds were grown following the assay methods of Graber et al.[6] of tomato plants in biochar. Biochar was added at a rate of 5% by mass (~20mL) to each of the test pots with a small measure leveled at the top. The biochar was mixed into the upper one inch of the growing mix[6]. For each of the four batches, 17 plants were grown and measured with the three-hour biochar amendment and 17 plants with the six-hour biochar amendment (Table 2).

Table 2. Number of germinated plants in the four batches and three treatments of biochar.

	Batch				Treatment
	1	2	3	4	
3 hours	17	17	16	17	67
6 hours	16	16	17	11	60
Ctrl (no biochar)					65

Sixty-eight control plants were also grown to correspond with the plants in the three- and six-hour treatments. Three of the control plants did not germinate, thus leaving sixty-five to record in the results. Control plant growth was carried out in the same manner as the test plants in the Pro-Mix All Purpose Growing Mix without biochar added to the soil.

Germination day was recorded as the day the first seedling shoot emerged visibly above the soil for each plant. Plant growth measures were recorded every 6 days: plant height, leaf number, and maximum leaf canopy diameter. Plant height was measured in cm from the base of the aboveground stem to the highest leaf point on the plant. Leaf number was recorded as the total number of leaves that met or exceeded 10 mm in length. Maximum leaf canopy diameter was measured in cm as the furthest distance from end to end of the leaf extensions on each plant. At the end of the 30 day growing period, total aboveground dry mass was measured for each plant.

Growth assay was stopped at 30 days because the plants would have needed transferring to larger pots. Dry mass was obtained by cutting the plants off at the base of the aboveground stem and drying the plants overnight at 105℃ in a Fisher Scientific Isotemp 725g Laboratory Oven. The dried plants were then weighed individually and the dry mass recorded in grams for each plant. Belowground root biomass was not collected due to time restraints.Time as well as space prevented growing the plants to maturity. Heavily root-bound plants such as tomatoes would need to be grown in much larger pots to allow for full plant growth and fruit-bearing.

Analysis was done using R statistical package[13]. Two analyses were performed due to the two-part nature of the study. To investigate if biochar had an effect on plant growth when compared to untreated plants, three-hour biochar, six-hour biochar, and control means were compared using one-way analysis of variance (ANOVA) or a Kruskal-Wallis Test when the data did not satisfy ANOVA assumptions. Sample sizes for these comparisons are indicated in the far right column (Treatments) in Table 2. Since there were no corresponding control batches with which to compare each of the biochar batches for analysis purposes, individual batches were not considered in this analysis.

To address batch consistency and variation in pyrolysis time, a two-way factorial ANOVA was used and controls were excluded. These sample sizes are indicated in the (Batch) columns 1-4 in Table 2. Controls were not used in these analyses because there were no analogous batches of controls against which to compare the biochar batches.

ANOVA assumptions were examined using box plots, quantile-quantile plots, and Levene's Test for homogeneity of variances. The emergence day, final dry mass, and growth rate by batch data were natural log transformed to improve their normality or if there were unequal variances for the different groups. Once assumptions were met, the ANOVAs were computed using Type II sums of squares due to unequal sample sizes. ANOVAs for emergence day by batch and treatment, final dry mass by batch and treatment, growth rate by batch and treatment, as well as emergence day by treatment were computed using R package DescTools[15]. One-way nonparametric tests of equality of means were computed using the Kruskal-Wallis Test. A Kruskal-Wallis test was used for both emergence day and final dry mass because the variances of the groups were significantly different according to Levene's Test. The Kruskal-Wallis test compares the medians, not means, but means will be discussed for consistency in data visualization.

Soil nutrient tests were done on the Pro-Mix All Purpose Growing Mix (control) and all four batches of the three and six-hour biochar products using a LaMotte Soil Analysis Kit (Model no. 5008). A biochar/soil mix was not tested because the mixing rate was so low, and the suspension of the biochar/soil mix was not able to be prepared. Nutrient content in parts per million (ppm) for chloride, phosphorus, nitrate nitrogen, potassium, and nitrite nitrogen, as well as pH of each batch and treatment were determined.

3. Data

There were no significant differences found between the biochar treatments or batches in nutrient content. In comparing the nutrient content of the three and six-hour treatments, the following statistical results were obtained: chloride (p=0.083); phosphorus (p=0.157); nitrate nitrogen (p=0.564); potassium (p=0.564); nitrite nitrogen (p=1.0); pH (p=1.0).

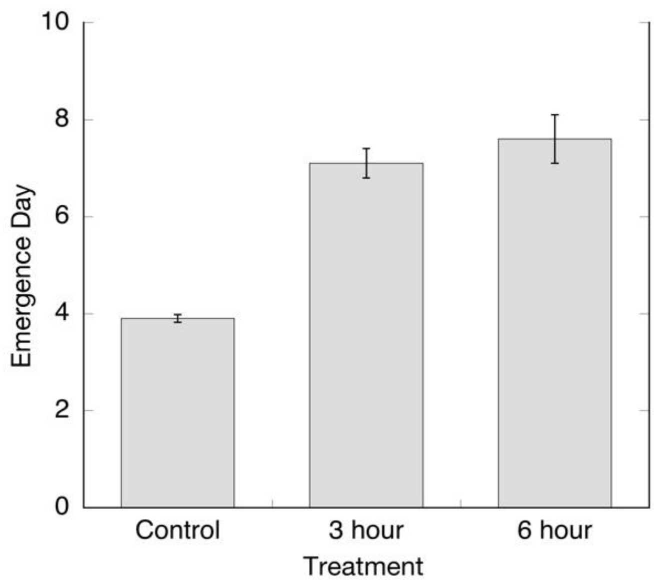

Fig. 2. Mean day of *Solanum lycopersicum* seedling emergence by treatment. Kruskal-Wallis Chi-squared: p<0.0001, X^2= 114, d.f.= 2. Error bars are ±1 SE.

The emergence day depended on which treatment the plant received (Fig. 2). Control plants emerged significantly earlier than the three hour and six-hour pyrolysis treatments. Emergence was almost twice as early in the control plants, at 1.36 (±0.171) days on average, as in both the three-hour treatment, at 1.91 (±0.303) days, and the six-hour treatment, at 1.95 (±0.361) days on average (p<0.0001).

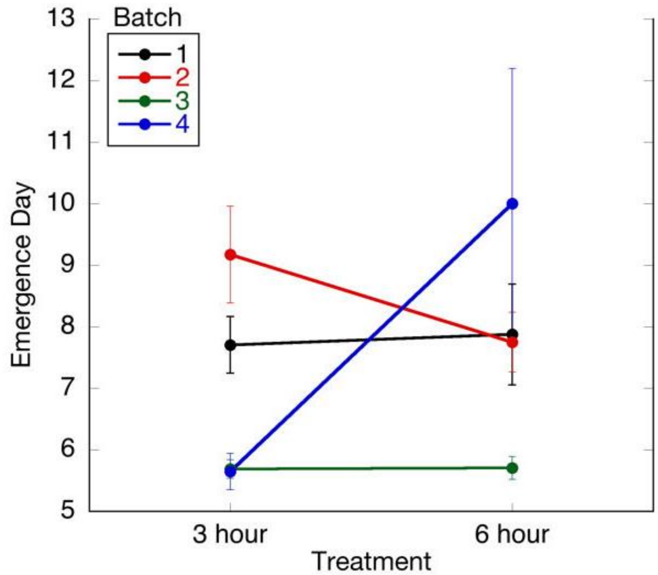

Fig. 3. Mean day of *Solanum lycopersicum* seedling emergence by batch. Analysis of variance: p= 0.003, F= 4.8, d.f.= 3, 119. Error bars are ±1 SE.

There was significant batch by treatment interaction in emergence day when only the biochar treated plants were considered (p<0.003; Fig. 3). For example, batch 4 plants emerged before day six in the three-hour treatment but emerged on day ten on average in the six-hour treatment. The effect of the biochar by batch cannot be distinguished without also discussing the treatment received.

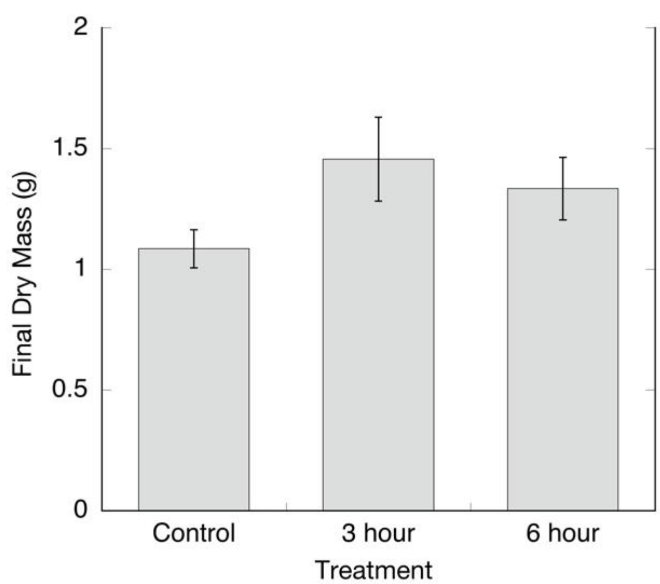

Fig. 4. Mean final dry mass of *Solanum lycopersicum* (g) by treatment. Kruskal-Wallis Chi-squared: p= 0.71, X^2= 0.694, d.f.= 2. Error bars are ±1 SE.

When averaged over all batches, aboveground dry mass at 30 days did not differ significantly among control, three-hour, and six-hour treatments (p< 0.71; Fig. 4).

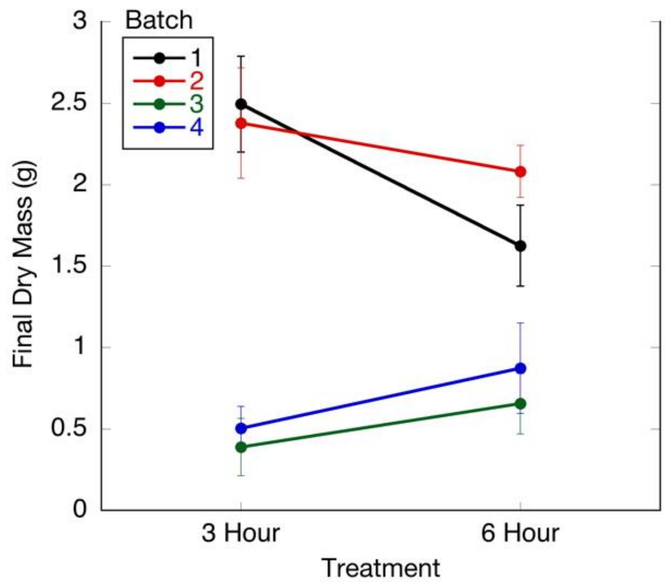

Fig. 5. Mean final dry mass of *Solanum lycopersicum* (g) by batch. Analysis of variance: p= 0.065, F= 2.46, d.f.= 3, 119. Error bars are ±1 SE.

Ignoring control data, there was marginal interaction between batch and treatment for final dry mass (p= 0.065; Fig. 5). Batches 1 and 2 had a larger final dry mass in the three-hour treatment and a smaller final dry mass in the six-hour treatment. Batches 3 and 4 showed the reverse, a smaller final dry mass at three hours and larger final dry mass at six hours.

The slope of the height versus time regression was used for each plant as a measure of overall growth rate. Linear regression was used because it was the best fit for the data based on height of each batch versus days after planting for both the three hour and the six hour treatments. Plant height was highly correlated with leaf canopy diameter and leaf number measurements, and thus was used as a summary measure for growth rate. Growth at each day of measurement was recorded and used to find the height growth rate in millimeters per day for each plant.

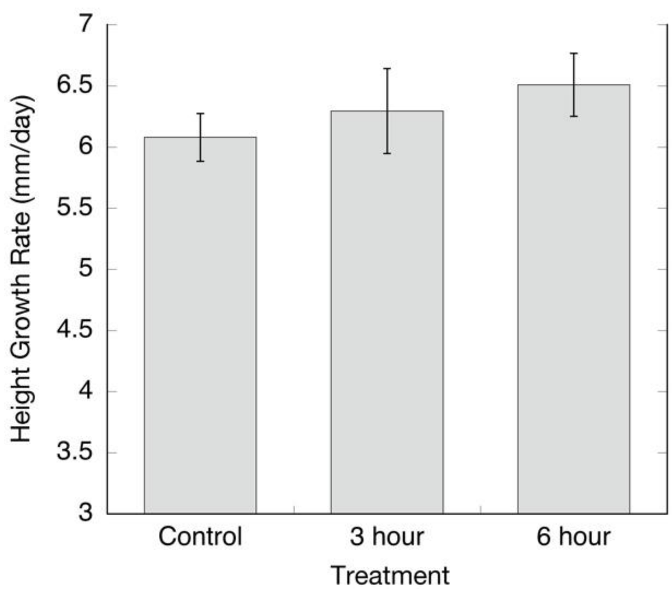

Fig. 6. Mean height growth rate (mm/day) of *Solanum lycopersicum* by treatment. Analysis of variance: p=0.56, F= 0.582, d.f.= 2, 188. Error bars are ±1 SE.

Mean height growth rates (mm/day) did not differ significantly among control, three-hour, and six-hour treatments ($p = 0.56$; Fig. 6).

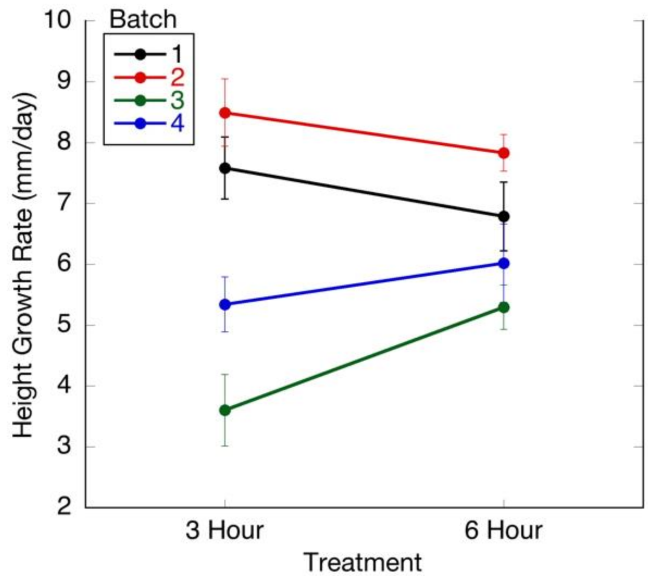

Fig. 7. Mean height growth rate (mm/day) of *Solanum lycopersicum* by batch. Analysis of variance: $p = 0.039$, $F = 2.88$, d.f.= 3, 118. Error bars are ±1 SE.

There was significant interaction between batch and treatment for height growth rate when controls were not considered ($p = 0.039$; Fig. 7). Batch by treatment effects interacted and quality of the batches cannot be determined without also specifying the treatment the batch received.

Growth rate was higher in the later emerging biochar plants. Some outliers were removed from the data to better indicate the overall trend. For the three-hour treatment, one plant emerged very late and grew very slowly. This data point was removed and the data fit the regression line much more closely; there was an r^2 increase from 0.19 to 0.31 after removal of the outlier.

In the six-hour treatment, three plants varied greatly from the overall trend of the regression line. These three data points were removed and the coefficient of determination was again improved; the r^2 increased from 0.013 to 0.25 after removal of the outliers.

There were no outliers in the control data and no control data points were removed for the analyses.

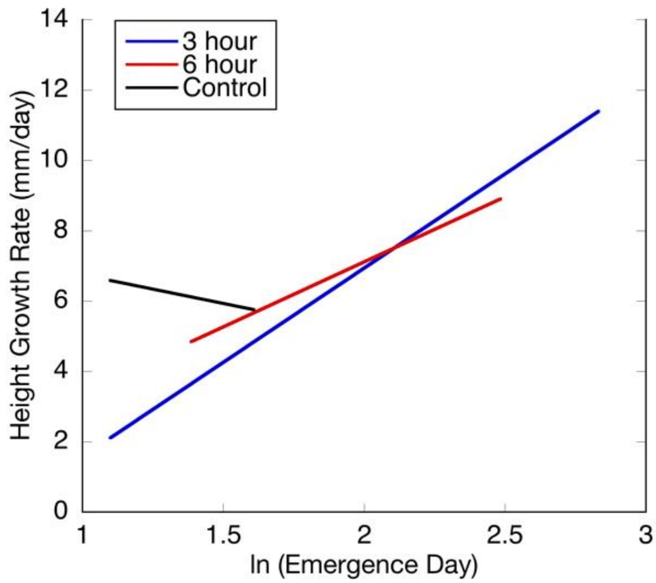

Fig. 8. Relationship between height growth rate (mm/day) and ln (Emergence Day) of *Solanum lycopersicum* for three-hour [height growth rate = -3.7819 + 5.3577x, r^2 = 0.308], six-hour [height growth rate = 1.5018 + 2.724x, r^2 = 0.185], and control [height growth rate = 8.3539 – 1.6118x, r^2 = 0.038].

With the outliers removed, all regression lines graphed together displayed that the control plants emerged early and mostly together, where the three and six-hour biochar plants emerged over a wider range of days (Fig. 8).

The relationship of natural log of emergence day and slope of the height regression line indicates that the later emerging biochar plants grew fastest. The earlier the biochar-treated plants emerged the slower they grew. The later the emergence the higher the growth rate. As a result, all treatments (control, three-hour, six-hour) were not significantly different in size at 30 days. The slopes of the height regression lines significantly differed between the control and biochar treated plants. The biochar treated plants displayed regression lines that were significantly more positively correlated with the emergence day. The control height slope regression lines were not correlated with the emergence day. These results were complex due, again to interaction effects.

4. Discussion

More research is needed to answer the first question posed (can food waste biochar be made into an effective fertilizer?). The biochar amended plants had later germination days on average, but had no significant differences in final height, final aboveground dry mass, or overall growth rate. The biochar, when compared to the soil used for the controls plant, did not improve plant height produce taller plants on average or statistically taller plants by the end of 30 days. As a fertilizer, this product would not be recommended based on these results. However, the later germinating biochar plants grew faster, indicating that more research is needed to answer this question.

The answer to the second question (does the effect of biochar vary among batches of food waste or pyrolysis time?) was complicated because of the many interacting results. No conclusion could be made about the individual biochar batches without also specifying the pyrolysis treatment that the batch received; vice versa, no conclusion could be made about the effect of pyrolysis time without discussing the individual biochar batches of that treatment as well. Without assigning quality or significant patterns to the results, it does appear that the properties of the biochar did vary by batch.

Energy inputs for the three and six-hour batches were relatively low. The Fisher Scientific Isotemp 725g Laboratory Oven is a 1300 kW, 120V oven. To pyrolize at 260℃ for three hours used 3.90 kWh of energy. At an average of \$0.12 per kWh nationwide (c. 2016), this is \$0.16 per hour or \$0.47 total spent on energy in each batch. This process released the same amount of greenhouse gases as driving a car for 10.3 km (6.4 miles). To pyrolyze at this temperature for six hours used 7.8 kWh of energy, and this cost \$0.94 per batch. This would release the same amount of greenhouse gases as driving a car for 20.6 km (12.8 miles). Overall, the amount of energy needed to produce the biochar was not insubstantial, but biochar may be better overall for the environment than the production and application of commercial fertilizers.

The mean emergence day of the control plants was earlier than the three and six-hour treatments. Previous studies have found biochar can have different properties, such as pH and particle size, which can interact with different soil types in many ways. Sun et al.[18] found that the production method had a strong effect on the biochar properties. Yet, across all methods, they did not find a significant effect on seed emergence and, thus, were able to use their biochar as a soil amendment. There are also many variables in biochar production. Biochars with different properties can be developed by adjusting these production conditions to meet certain application needs[18]. These results might have been improved by utilization of a biochar product engineered for beneficial application in greenhouses or with tomato plants.

The pyrolysis temperature or duration in this study may have produced biochar with poor seed-starting ability and the presence of inhibitory hydrocarbons. There was variation among batches in emergence day and interaction with both the three and six-hour treatments, thus, no qualification indicating which of the batches or two treatment types was better could be made. In future comestible plant or crop application, emergence tests can be done to assess the viability and quality of the biochar as a fertilizing soil amendment[18]. Moreover, some additional amendment may need to be added when using certain biochars to aid in improving emergence. It is also known that soil oxygen content can affect germination time[4]. As this was not measured in the biochar amended soils and compared to the controls, this factor may have also impacted the days to germination if soil oxygen amounts were not ideal.

Due to interacting batch and treatment effects it is not known if the differences in height at the end of the study were caused directly by emergence day or indirectly by biochar and its effect on growth rate. However, due to significantly earlier emergence days, the control plants were taller at each day measured. Mean height growth rate was used to see the effect of biochar on growth rate compared to controls. The growth rate for all plants takes into account the effects of any emergence day and final height or dry mass differences between control and biochar plants. This revealed that the earlier the biochar plants emerged, the faster the growth rate. There is some unexplained effect of biochar on the plants. This caused the plants that emerged last to have an accelerated growth rate over the earlier to emerge plants, and to reach final heights that were not significantly different than the control, and earliest emerging biochar plants.

It was expected that growth rates would be the same regardless of emergence, so the later the emergence day the shorter the final expected height at 30 days. However, all treatments produced the same final height regardless of emergence. Growth rates may have been affected in different ways not measured by these analyses. There may also have been more pronounced differences had these plants been grown to maturity and assessed for their ability to bear fruit. It has been found that certain biochars improve nutrient retention through cation adsorption in the soils and limit the amount of fertilizers leached into runoff water[2,9,10]. This might mean that the short growing window of this study provided insufficient time for the release of nutrients from the biochar, and that on day 30 some of these slow-release benefits may have only just begun becoming evident. A longer growth period may be required to observe any other beneficial effects from all batches and treatments of the biochar when compared to the control plants.

Biochar did not significantly affect aboveground dry mass at 30 days. Belowground biomass allocation may have been different in the biochar and control plants, and this might have been affected by certain properties of the biochar. Generally, plants respond to a decrease in belowground resources with increased biomass allocation into roots. Poorter and Nagel[12] found that the response of plants to available nutrients follows this functional equilibrium hypothesis. Muller et al.[11] found that biochar amended plants allocated less to aboveground mass (i.e. stems and leaves) in low-nutrient conditions than in soils of high nutrient concentration. The larger amounts of aboveground dry mass in some batches may have been affected by the growth conditions of this study and the relatively low amount of available nutrients.

There were many complex interactions in this study and there is much yet to learn about how individual batches of food waste biochar affect plant growth. The complex effects of biochar on emergence and growth rate suggest that growing plants to maturity may have demonstrated clear size effects. This might also allow for the biochar amended plants to yield the benefits and show signs of the slow-release fertilizing effect found in other biochar studies. Also, a further exploration of the interactions of soil properties with biochar application would be beneficial.

Biochar had an effect on emergence day but not on final aboveground dry mass or average growth rate. There was variation in the biochar due to batch and pyrolysis treatment. However, no final conclusions on quality can be made due to many complex interactions. The effect of each batch interacted with the effect of pyrolysis time in different ways depending on the type of plant measurement analyzed. This made any conclusion of which batch or pyrolysis treatment was superior impossible without specifying both batch and pyrolysis treatment. The biochar did not appear to be an effective fertilizing soil amendment.

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