Evaluation of green waste biochar and hydrochar application as soil amendment

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Abstract:
Purpose: This study evaluates the potential application as growth substrate or soil amendment of fresh hydrochar (FHC; obtained after hydrothermal treatment of garden and park waste (GPW) at 180 ºC 1h); post-treated hydrochar (washed (WHC), aged (AHC), and thermally treated (THC)), as well as biochar (BC; obtained after pyrolysis of GPW at 900 ºC 90 min) for their potential agronomic application.
Methods: The effect of mixing fresh hydrochar (1-5 %) with growth substrate (composed by peat, vermiculite and/ or sand), on *Arabidopsis thaliana*, *Chenopodium quinoa* and *Solanum lycopersicum* (tomato) seed germination index (GI), fresh weight (FW), and dry weight (DW) was determined. Moreover, 1-5 % of FHC, WHC, AHC, THC, and BC were applied to a marginal agricultural soil to establish their effect on *Solanum lycopersicum* seed germination, and determining their potential phytotoxic effects.
Results: FHC complies with legal regulations and presents good chemical characteristics for its application as soil amendment. Nevertheless, its application on peat-based substrates, especially those containing sand, caused inhibition of both, germination and plant growth. Application of each post-treated HC on the agricultural soil alleviated the germination inhibition and even slightly improved the control GI at low dosages (1 %) in WHC, THC and BC.
Conclusions: Taking into account the technological and economical requirements of the procedure, washing resulted in the best HC post treatment before application on soil for germination.

Keywords: biochar, germination index, hydrochar upgrading, soil amendment.

1. Introduction

Biomass has been largely thermally processed into biochar, a solid product rich in carbon used for a diverstity of applications such as biofuel, contaminant remediation and soil amending [1]. Biochar (BC)is produced by a well established technology: pyrolysis. However, circular economy development based in waste valorization must be constructed not only in proven technologies but also in emerging ones for the production of value-added materials. Hydrothermal treatment (HTT) is a promising technology to achieve the goal of comprehensive utilization of biowaste to produce an emerging type of BC sythesized at lower temperature (180 – 250 ºC) than pyrolysis, called hydrochar (HC) [2]. Although HC can be used for the same purposes as BC, its effectiveness in similar applications needs to be tested and compared, due to the their different physicochemical properties [1], such as higher O/C and H/C ratios, resulting in a lower of aromaticity as well as a poor stability when is added to soils [2]. HC has also been demonstrated to contain abundant oxygen-containing functional groups [3].

Common and natural raw feedstocks are usually utilized for BC and HC production such as sewage sludge, plant residues, wood chip, livestock manure [4–7]. Garden and park waste (GPW) constitutes a highly available resource at municipalities, being currently treated in composting or anaerobic digestion processes, resulting in low added-value product (compost) or low production (biogas) owing to its structural complexity [8].

Degraded soils generally show poor physical characteristics in texture, structure, porosity, bulk density, and water holding capacity. Biochar and HC amendment might effectively increasing soil porosity [9], decreasing bulk density [10], and promoting the formation and stability of soil aggregates [11]. The HC application can also improve nutrient availability, and crop productivity within the framework of sustainable agriculture. These positive changes have been observed in soils of different textures, such as clay soils [10], sandy soils [9], and loamy soils [12]. However, the effects of interactions among soil components such as soil organic carbon, minerals, and microorganisms with HC particles on soil physical properties are still unclear [13]. Moreover, huge knowledge gaps regarding the responses of soil chemical and biological properties to the application of HC should be further considered to determine the effect on C sequestration, or bioavailability and toxicity of contaminants [14]. Therefore, research efforts are needed to reveal the relationships between HC characteristics and the responses of different crops.

It is of special interest to evaluate the optimum dosage for a given crop in a specific soil. In addition, recent studies have shown that fresh HC (FHC) applied to the soil, can have a short-term negative effect on plant germination and growth, probably due to the presence of several toxic substances on its surface, such as furfural, PAH, organic acids and phenols, among others. Therefore, a post-treatment to remove organic phytotoxic compounds would be desirable. A reduction of, biodegradable compounds, phytotoxic effects, and plant available nutrients has been observed after HC washing [15]. A decreased inhibition effect was observed after aging post-treatment, probably due to microbial degradation of HC components and a consecutive immobilization of mineral nitrogen [2,16]. Hiztl et al. [17] determined phytotoxicity elimination from HC after thermal treatment (200 – 600 °C). In addition, some post-treatments can also modify the textural properties of the HC, providing a more advanced material [16,17].

The aim of this study has been to evaluate the potential application as growth substrate or soil amendment of FHC, post-treated HC and BC obtained from GPW. Two experiments have been designed. The first one to evaluate the effect of (2 – 15 %) FHC on the plant-substrate seed by test germination index (GI) and plant growth of *Arabidopsis thaliana*, *Chenopodium quinoa* and *Solanum lycopersicum* (tomato). Moreover, the evaluation of different physiological parameters (fresh weight (FW) and dry weight (DW)) was determined. The second one analyzed the effect of adding 1 – 5 % of FHC, WHC, AHC, THC, or BC to a marginal agricultural soil to establish their effect on *Solanum lycopersicum* seed germination to determine their potential phytotoxic effects.

2. Material and Methods

2.1 Hydrothermal carbonization, pyrolysis and post-treatments

Raw feedstock: The GPW, collected from municipal parks, yards, and gardens of *Comunidad Autónoma de Madrid* (Spain) and containing leaves and tree branches was ground and sieved to reduce and homogenize the particle size. After that, it was dried at 100 ºC for 48 h in a convection oven and stored in airtight containers until used.

Fresh hydrochar: 1kg of GPW (20 % GPW / 80 % deionized water (w/v)) was subjected to HTT in a 4 L ZipperClave 316 stainless steel pressure vessel at 180 °C [6]. The obtained slurry was separated into liquid and solid fractions by filtration (0.45 µm). The obtained HC was dried at 100 ºC for 48 h in a convection oven.

Biochar: 200 g of raw feedstock were pyrolyzed in a rotatory tube furnace, (CARBOLITE HTR 11/150), equipped with a quartz tube (15 cm x 21 cm) at 900 ºC for 90 min (heating ramp of 3 ºC/min and N_2 purge (with a flow rate of 1 mL/min) to ensure an oxygen-free atmosphere).

The characterization of the feedstock, FHC and BC (moisture, ash, volatile matter (VM), and fixed carbon (FC)) was performed by thermogravimetric analysis according to ASTM-D7582 [18] in a thermogravimetric analyzer Discovery SDT 650. Their elemental composition (C, H, N, and S) was determined on a CHNS analyser (LECO CHNS-932), following the standard manufacturer procedure and mineral elements were quantified by inductively coupled plasma atomic emission spectroscopy (ICP-MS) on an Elan 6000 Sciex instrument (Perkin Elmer), following the standard manufacturer procedure. The pH and EC were analysed following Manzano et al. [19].

Moreover, the FHC was subjected to different post-treatments:

- Aging: Bulk samples of FHC were placed on trays with a maximum height of 4 cm and periodic turning were performed for four months at room temperature to allow their maturation by air exchange, obtaining as a product aged hydrochar (AHC).
- Washing: FHC was washed with deionized water at the ratio of 1:10 (w:v). The suspensions were shaken at 120 rpm for 1 h, followed by centrifugation and filtration. The washing procedure was repeated thrice to obtain the washed hydrochar (WHC).
- Thermal post-treatment: the FHC was thermally treated (THC) at 650 ºC for 90 min in the oven previously described.

The resulting solids were dried at 105 ºC for 24 h, ground to a particle size of 3 mm and stored in zip lock bags for further characterization. The determination of moisture and organic matter (OM) was carried out following standardized methods [20,21].

2.2 Mixture design

In the experiment using FHC with substrates, 4 mixtures with different compositions were prepared assuring homogeneity as indicated in **Table 1**. S1 a moderately decomposed white peat TS3 from Valimex S.L. In S2 peat TS3 and river sand, a coarse fraction of soil minerals which can serve as diluent to more reactive components in plant growth media [22] were mixed. In S3 peat TS3 and vermiculite Nº 2, a mineral that aid to the soil aeration [22], provided by Projar (Valencia, Spain) was used. In S4 the three components described were mixed in the proportions indicated in Table 1.

Table 1. Substrate composition including FHC concentration and sterilization conditions.

Substrate name	Composition (% d.w.)			Concentration of FHC (% d.w.)	Autoclave conditions (T; t)
	Peat	Vermiculite	River sand		
S1	100	-	-	Control, 2.5, 5 and 10	115 ºC; 15 min
S2	80	-	20		
S3	75	25	-	Control, 2, 2.5, 5 and 10	120 ºC; 40 min
S4	60	20	20		

The substrates were characterized following UNE standard methods for soil amendments and growing media including pH, electrical conductivity (EC), cation-exchange capacity (CEC), OM, and moisture [20,21,23–25]. Total Kjeldahl nitrogen (TKN) using standard analytical methods [26] Moreover, oxidable OM was determined by the Walkley-Black method [27], and P content was quantified by inductively coupled plasma atomic emission spectroscopy (ICP-MS) on an Elan 6000 Sciex instrument (Perkin Elmer), following the manufacturer procedure.

A marginal agricultural sandy loam soil from vineyards of Burgos (Spain) with 1 % of OM, low concentration in clay (8 %), and pH of 8.4 was used to study the effect of washing, aging and thermally post treating FHC. Moisture and OM were determined as previously mentioned [20,21]. Mixtures of soil with different percentages (1, 3, and 5 % D.W) of BC, FHC, WHC, AHC, and THC were prepared and, after stabilization, pH and EC was determined.

2.3 Biological assays

2.3.1 Germination and growth test using peat-based substrates with fresh hydrochar

Peat-based substrates were employed in the first assay. Three different plant species were used: *Arabidopsis thaliana* –ecotype Columbia, obtained from María Reguera´s laboratory (Universidad Autonoma de Madrid, Spain), *Chenopodium quinoa (quinoa)* – variety F16 provided by the company ALGOSUR S.L. (Seville, Spain)- and *Solanum lycopersicum* (tomato) –variety Marmande RAF type provided by Semillas Batlle S.A. (Catalonia, Spain).

Arabidopsis thaliana tests were carried out in square 8 x 8 x 8 F thermoformed pots (Projar, Valencia, Spain), while quinoa and tomato were grown in round short, thermoformed pots of 10.5 cm (Projar, Valencia, Spain). All pots were filled with the same weight of substrate mixture and then, they were watered to

promote seed germination. Thirty to forty *Arabidopsis* seeds, 8 seeds of quinoa, or 10 seeds of tomato were sown on the surface of the corresponding pot. *Arabidopsis* was tested with the four substrates with a FHC concentration on dry weight (d.w.) of 2.5, 5 and 10% on S1 and S2 and 2, 2.5 and 5 % on S3 and S4. Quinoa and tomato were tested with S3 and S4 using 2.5, 5 and 10 % of FHC (d.w.). All assays were performed in triplicate using the substrate without HC as control. The pots were covered with plastic film to avoid water evaporation and were kept at 4 °C for 72 h in the dark prior to each experiment to ensure seed stratification. Then, the pots were transferred to a controlled plant growth chamber set at 24 °C/18 °C with a 12 h/12 h, light/dark photoperiod (with a light intensity of 120 µmol m^{-2} s^{-1}). The plastic film was removed 5 d after sowing.

The GI, calculated following equation 1, and leaf area, calculated after taking images of the leaves and by analyzing them using the *ImageJ* software available online (https://imagej.nih.gov), were recorded every two days. To evaluate plant biomass at the end of the experiment, plants were cut at stem level with soil at 21 d and 43 d after showing (DAS) for tomato and quinoa, respectively, and the FW was recorded. To determine the biomass DW, the fresh tissue was dried at 65 ºC for 72 h.

$$Germination\ index\ (\%) = \frac{grown\ cotyledons}{total\ seeds\ in\ pots} \times 100 \qquad \text{(Eq. 1)}$$

2.3.2 Germination assay using soil with biochar, fresh, aged, washed, and thermally treated hydrochars

Soil was mixed with BC as well as FHC, AHC, WHC, THC in different doses (1, 3 and 5 % DW). Petri dishes (9 cm of diameter) were filled with 45 g of each mixture. Bare soil was used as control. They were watered until 75 % water holding capacity and let to stabilize for one week in darkness at 28 ºC. Five replicates were prepared; one of them was used for pH and EC determination and the other four for seed germination. Tomato (*Solanum Lycopersicum)* seeds were surface sterilized and sown (10 seeds per plate). Plates were placed in a convection oven at 28 ºC for 3 d in darkness and then transferred to a growth chamber set at 26 °C/20 °C with a 13 h/11 h, light/dark photoperiod, where germination index was recorded after 5 d.

2.4 Statistics

The effects of HC concentration, type of substrate, and their reciprocal interactions on germination, fresh and dried biomass, and leaf area were analyzed by two-way completely randomized ANOVA on the FHC-substrates assays. Averages were separated by substrate type and the Tukey test was performedto means comparison at the 0.05 probability level. The statistical program Minitab (version 19) was used.

3. Results and discussion

3.1 Proximal and elemental analysis of feedstock, fresh hydrochar and biochar

The main physicochemical properties of raw-GPW and FHC are summarized in **Table 2**. Compared to feedstock, FHC showed a lower ash content but a higher mineral concentration except for K and Mg. Ca, K, and P are important macronutrients for plants growth and all of them are abundant in HC. Moreover, its high C content could be relevant for use as soil amendment especially in degraded soils with poor OM content. It is observed that a carbon-rich product is obtained after HTT with a proper C/N ratio for soil amendment, and low H/C and O/C ratios. The atomic H/C ratio is used as an indicator of the degree of aromatization, which in this case suggests a non-condensed structure, and the O/C ratio is indicative of the degree of carbonization [28]. FHC shows a less aromatic structure than the raw material with a large amount of carboxylic and hydroxyl groups. Thermal treatment enriched elementary content and lowered H/C and O/C ratios; however higher concentration of heavy metals which could have a negative effect on plant growth have been also determined [29]. The concentration of potentially toxic metals like Cr or Zn was under the maximum allowed for organic amendments in Spain (Cr ≤ 70 mg/kg and Zn ≤ 200 mg/kg) [30] (being categorized as a class A amendment suitable for the use on any vegetable crops.

BC presented similar moisture and total solid contents to the HC, but VM resulted in almost negligible while the ash content and FC increased compared to other feedstocks. C/N ratio decreased compared to raw

waste and resulted similar to FHC. Both H/C and O/C ratios were significantly lower than FHC and the raw waste due to the higher operation temperature.

Table 2. Chemical characterization of feedstock, fresh hydrochar, and biochar

	Raw GPW	FHC 180 ºC	BC		Raw GPW	FHC 180ºC
Moisture (%)	4.0	3.8	4.0	**Ca (mg/kg)**	5130	32700
Total solids (%)	96.0	96.1	96.0	**Si (mg/kg)**	7327	8630
VM (% d.w.)	76.5	67.1	6.3	**K(mg/kg)**	4860	3500
Ash (% d.w.)	5.1	3.3	22.6	**P (mg/kg)**	930	1162
FC (% d.w.)	18.4	29.6	71.1	**Fe (mg/kg)**	-	650
C (% d.w.)	46.9	49.8	70.5	**Mg (mg/kg)**	774	650
H (% d.w.)	6.1	5.3	0.8	**Al (mg/kg)**	123	367
N (% d.w.)	0.9	1.3	1.7	**Na (mg/kg)**	31	53
S (% d.w.)	0.4	0.2	0.1	**As (mg/kg)**	-	0.7
O (% d.w.)*	40.6	40.1	4.3	**Cd (mg/kg)**	-	0.5
C/N	60.8	44.6	48.4	**Co (mg/kg)**	-	0.4
H/C	1.6	1.3	0.1	**Cr (mg/kg)**	-	70
O/C	0.6	0.6	0.1	**Zn (mg/kg)**	20	29
N/P/K	0.9/0.9/ 4.9	1.3/1.1/3.5				

Each data point shows a standard deviation of ≤ 0.

* *O=100−C−H−N−S–ash (wt.%)).*

3.2 Characterization of peat-based substrates

Table 3 presents some physicochemical properties of the four growth substrates prepared. pH is related to nutrients availability/solubility being a key indicator; moreover, it affects microbial activity [31]. All substrates are acid, being 5.7 - 7.0 the optimal pH range for most plant growth [32]. EC shows soil salinity, thus a substrate with EC < 400 mS/m is considered no saline [33] and, therefore, it would not affect the fertility. CEC measures the soil's ability to retain nutrients; when soil presents a high CEC, more beneficial for nutrient retention favoring plant growth. As can be seen in **Table 5**, S1 and S3 showed high CEC, helping plant growth while sandy substrates presented low values.

Table 3. Physicochemical characterization of substrates.

	S1	S2	S3	S4
pH	5.19 ± 0.01	5.93 ± 0.01	5.48 ± 0.01	6.53 ± 0.01
EC (mS/m)	40.2 ± 0.1	15.7 ± 0.1	27.8 ± 0.1	31.4 ± 0.1
OM (%)	98 ± 1	15 ± 1	59 ± 1	15 ± 2
Moisture (%)	61 ± 1	22 ± 1	48 ± 1	24 ± 2
TKN (kg/kg)	0.37 ± 0.02	0.23 ± 0.03	0.32 ± 0.02	0.25 ± 0.02
P total (g/kg)	0.6 ± 0.1	0.5 ± 0.1	1.5 ± 0.1	1.2 ± 0.1
Oxidable OM (%)	46.5 ± 0.2	21.9 ± 0.3	46.9 ± 0.9	13.2 ± 0.8
CEC ($cmol^+$/kg)	866.0 ± 0.2	298.8 ± 0.2	900.8 ± 0.6	306.9 ± 0.2

OM content is also a key attribute in assessing soil health, generally correlating positively with crop yield [31]. S1 and S3 were enhanced in OM due to the absence of sand on mixture. OM favors water holding capacity. High OM percentages lead to higher moisture (**Table 3**) and extensive surface area that is responsible for high CEC [34].

Regarding to nutrient content TKN yielded a large N content in both, S1 and S3 substrates, due to the less sand and greater vermiculite and peat content which was fertilized by the distributing company. Regarding the P content, S3 and S4 are the most enriched substrates in P due to vermiculite [35].

3.3 Characterization of soil, biochar, fresh and post treated hydrochars

Table 4 sums up the main characteristics of the soil and different chars. FHC presented a neutral and proper pH for plant growth. Aged and washed HC had a similar slightly acidic pH while higher temperature involved in THC and BC induced a strongly basic pH. Lastly, mild basic pH was registered for the soil. BC, FHC and THC reported the highest EC values while AHC showed values close to the soil. Regarding to OM, values were related to operation temperatures.

Table 4. Physicochemical characterization of feedstock.

	FHC	AHC	WHC	THC	BC	Soil
pH	6.8 ± 0.1	5.5 ± 0.1	5.2 ± 0.1	11.2 ± 0.1	12.5 ± 0.1	8.4 ± 0.1
EC (mS/m)	1872 ± 6.2	90 ± 3.1	378 ± 7.4	1152 ± 9.6	993 ± 8.4	62.3 ± 4.3
OM (%)	96 ± 0.5	97 ± 0.9	94.6 ± 0.1	85.4 ± 0.4	84.5 ± 0.6	0.8 ± 0.2
Moisture (%)	3.8 ± 0.2	4.3 ± 0.2	3.2 ± 0.1	0.3 ± 0.1	3.9 ± 0.3	0.8 ± 0.1

Similar values of pH were registered among the stabilized mixtures for the control, FHC and AHC based treatments among all dosages tested (7.5 ± 0.1). WHC showed a slightly lower pH (6.8 ± 0.1) in all the cases. THC and BC mixtures reported a higher pH when higher dosage of char was employed rising from 7.2 to 8.1 and from 7.8 to 8.7, respectively. EC of all assays tested ranged from 149 to 224 mS/m and in every treatment increased when a higher dosage of chars was used.

3.4 Germination and growth test using peat-based substrates with fresh hydrochar

Figure 1 shows the time-course evolution of the germination index for *Arabidopsis thaliana*, using the four substrates studied. The type of substrate, as well as the FHC concentration, caused significant differences in germination indexes ($p<0.001$), being higher when using substrates without vermiculite (S1, S2). The increasing concentration of FHC negatively affected the germination index when S1 and S2 substrates were used. In the case of S2, a significant decrease was reported at dosages above 2.5 % while in S1 a smooth decrease was registered in all the treatments tested. The GI resulted lower when S3 and S4 were used compared to the previous substrates. S4 with 2.5 % reported unusual low GI compared to the rest of treatments tested due to mold appearance.

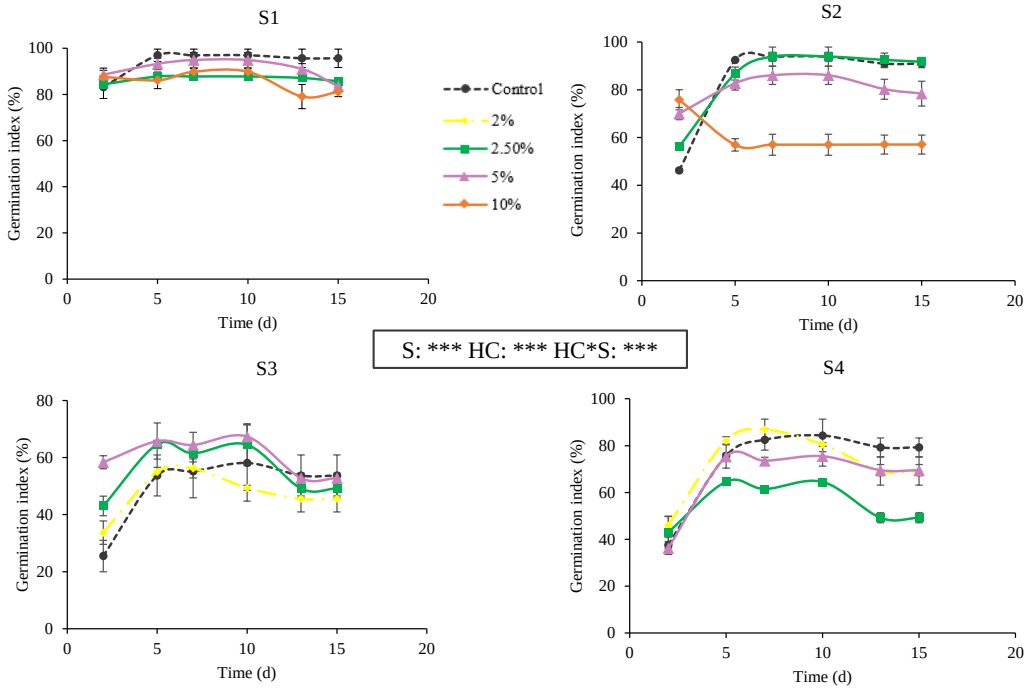

Figure 1. Germination index of *Arabidopsis thaliana* on different mixtures substrate-HCF during time. ***:p<0.001.

As observed in **Figures 2 and 3** in which the germination time course of tomato and quinoa seeds are presented, respectively, both species presented a delay in germination under increasing concentrations

of HC. Nonetheless survival rates of both species were higher compared to *Arabidopsis*, demonstrating that *Arabidopsis* is more sensitive than tomato or quinoa to HC treatment. Tomato GI (**Figure 2**) was affected by the FHC concentration ($p<0.05$). While in S3 substrate the germination index increased with increasing FHC concentrations, a high FHC concentration caused a reduction in S4 substrate. In the case of quinoa GI (**Figure 3**), differences between substrates ($p< 0.001$) (with 20-40 % decrease observed for S4), and FHC concentrations ($p<0.05$) were registered. The GI using S3 did not present significant differences between treatments but the increase of FHC concentration in S4 resulted in the germination index decrease as occurred with tomato. Bargmann et al. [36] suggested that the barley seed germination inhibition could be caused by the adsorption of dissolved organic compounds on HC, like guaiacol, levulinic and glycolic acids which may have phytotoxic effects. Puccini et al. [37] also demonstrated negative effects of HC on germination due to a high content of potentially phytotoxic substances such as volatile fatty acids and phenols.

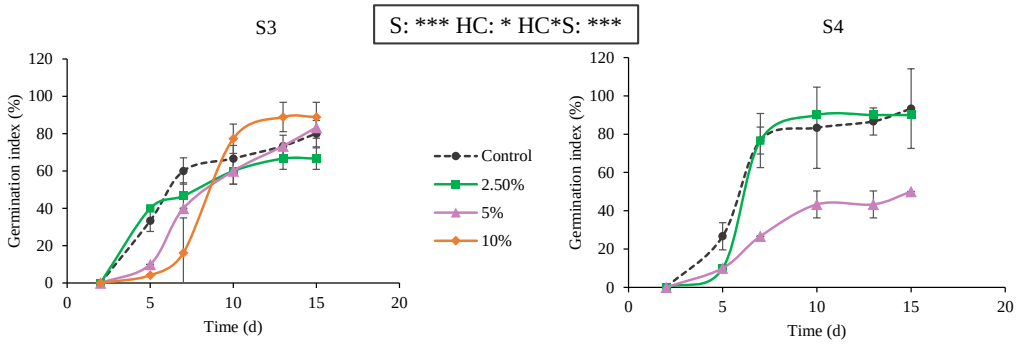

Figure 2. Germination index of tomato on different mixtures substrates-HCF during time. **: p<0.05

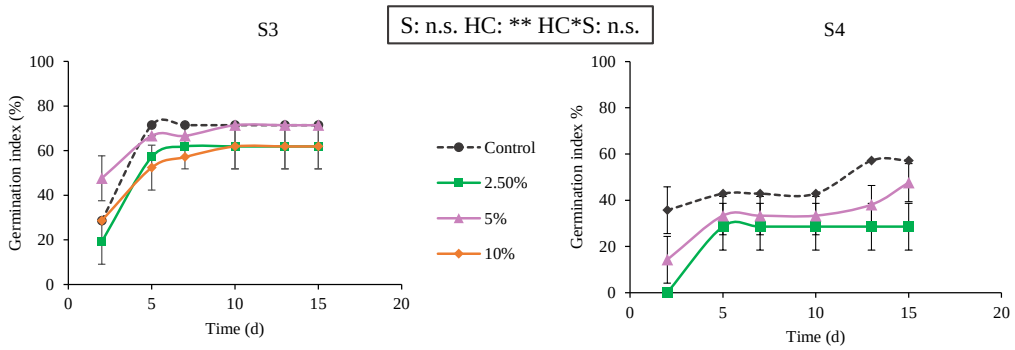

Figure 3. Germination index of quinoa on different mixtures substrates-HCF during time. ***: p<0.001. *: p=0.05.

Figure 4 shows the influence of FHC concentration on *Arabidopsis* growth by evaluating changes in leaf area. The presence of FHC negatively affected the leaf area regardless of the concentration used in substrates S2 and S4. This could be due to the water repellence of sandy soils preventing the nutrients absorption by the plant. S3 showed the greatest growth probably due to the vermiculite presence that may provide a higher moisture retention and aeration. Regarding the FHC concentration, plant grown in S3 2.5 % shown a similar trend than the control, while the use of the other three substrates implied a significant decrease compared to control.

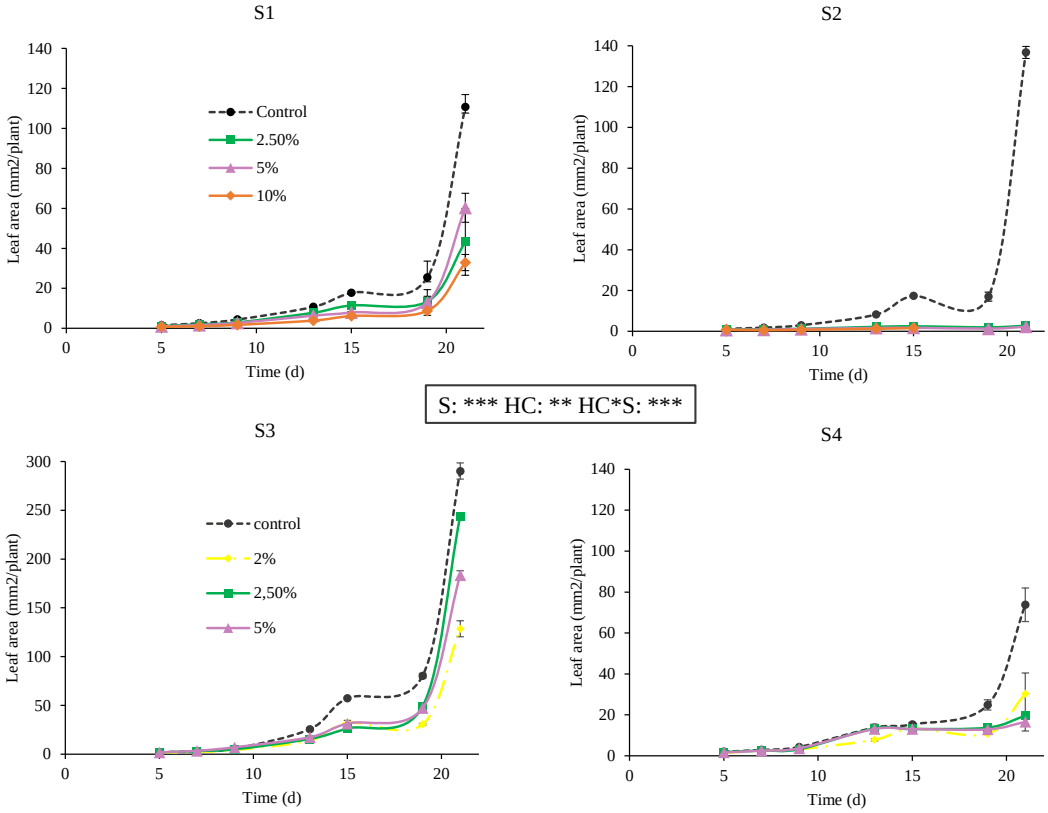

Figure 4. Leaf area *of Arabidopsis thaliana* on different mixtures substratre-HCF during time. ***: p<0.001; **: p=0.01

Even though the germination results in tomato and quinoa were promising, especially using S3 substrate, plant growth inhibition was observed when FHC was added into the soil. Presence of sand in the mixture increased water drainage resulting in a soil lower water retention. Therefore, great differences were observed in fresh weight among substrates, affecting in plants water holding capacity (**Figure 5 and 6**). The presence of HCF had a negative impact on growth for both tomato and quinoa worsening as the dosage increased especially in quinoa grown on S4 where dosages of 2.5 % caused a reduction upon control similar to the 5 % treatment tested in S3 as can be seen in **Figure 6**. George et al. [38], described a mild decrease in root and shoot biomass, affecting *Medicago sativa* growth. Schimmelpfennig et al. [39] also observed a significant reduction of *Lolium perenne* biomass related to the phytotoxicity of volatile organic components present in the FHC and/or microbial immobilization of N resulting in a limiting N availability for the plant.

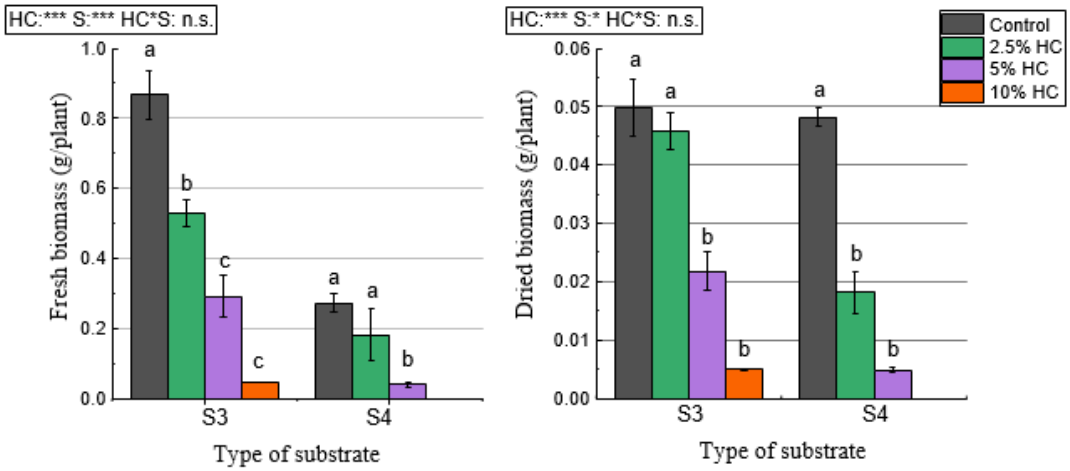

Figure 5. Fresh and dried biomass of tomato after 21 DAS. Bars with different letter indicates significant diferences. ***: p<0.001; **: p=0.01; *: p=0.05; n.s.: no significant.

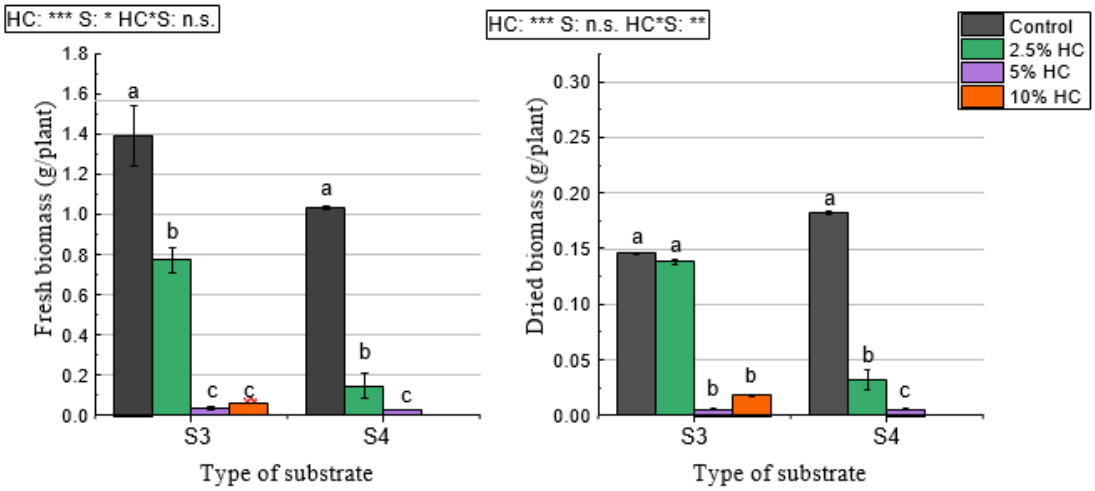

Figure 6. Fresh and dried biomass of quinoa after 43 DAS. Bars with different letter indicates significantdifferences. ***: p<0.001; **: p=0.01; *: p=0.05; n.s.: no significant.

3.5 Germination assay using soil with biochar, fresh and post-treated hydrochars.

Figure 7 shows the GI for tomato using biochar, fresh and different post-treated chars mixed with the marginal agricultural soil. Most of the HCs tested showed no inhibitory effects on tomato germination. Only FHC caused a significant reduction in GI for doses higher than 1 %. Metanalysis carried out by Luutu et al. [40] also reported severe germination inhibition above 2.5 % (w/v) when using GPW fresh hydrochar. WHC and BC mixtures slightly improved the GI. THC also improved it at low dosage (1 %) and at higher proportions did not present negative effects on GI. AHC did not showed negative effects upon GI at any dosage. Finally, AHC did not showed negative effects upon GI at any dosage. As observed by Islam et al. [41] on lettuce germination these results suggest that the post treatments of FHC reduce the germination inhibition.

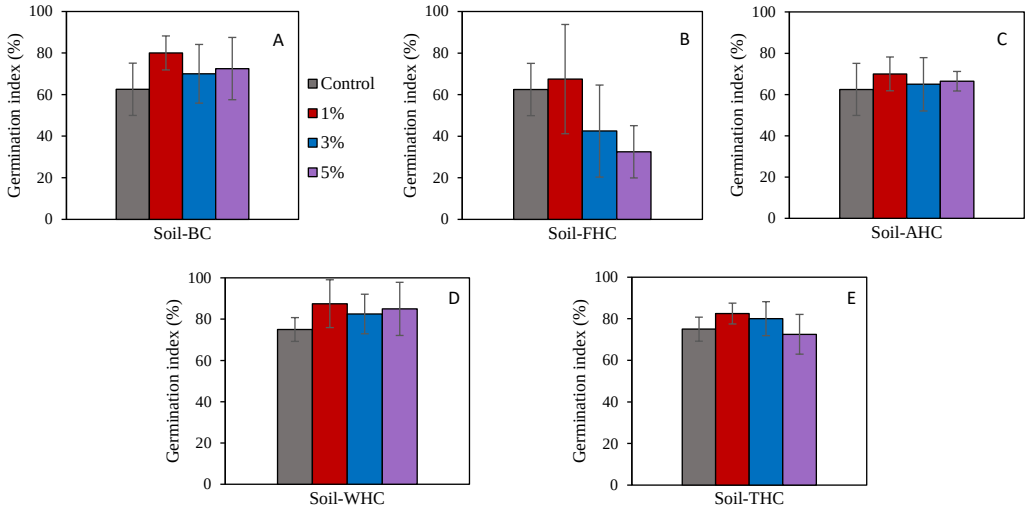

Figure 7. Germination index 5 days after germination of tomato using BC (A), FHC (B), AHC (C), WHC (D) and THC (E).

4. Conclusions

HTT results in an effective method for valorizing lignocellulosic residues to produce an HC that presents good chemical characteristics to be used as soil conditioner, such as high C and nutrients (N, P) content, and low toxic metals content (below regulated limits).

However, the application of HCF obtained from HTT of GPW at 180 ºC on peat-based substrates, especially those containing sand, caused inhibition of both, germination and plant growth, in the model organism *Arabidopsis thaliana* and in tomato and quinoa crop plants.

However, in the germination of tomato seeds on marginal agricultural soil and char mixtures, all post treatments of FHC tested alleviated the germination inhibition shown by FHC at high dosages Considering the celerity and techno-economical requirements of the procedure, WHC resulted in the best post treatment before application on soils for germination.

Acknowledgments

The authors greatly appreciate funding from MICINN (PID2019-108445RB-I00), MINECO (PDC2021-120755-I00) and financial support from Madrid Regional Government (Project P2018/EMT-4344). E. Suarez received additional funding from Madrid Regional Government (PEJD-2019-PRE/AMB-14231).

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