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REVIEW PAPER

# Hydrochar-based soil amendments for agriculture: a review of recent progress

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**Abstract**

Hydrochar is a carbon-rich material produced by the hydrothermal carbonization (HTC) of biomass. As a new concept, hydrochar has generated much research interest due to its ability to employ wet and dry biomass as feedstocks and its application in the agronomical, environmental, and energy sectors. This review considers the developments made with hydrochar as a soil amendment in terms of soil fertility, carbon sequestration, and fate of pollutants based on the available data. Moreover, the economic feasibility using a life cycle assessment of hydrochar has also been discussed. This review assessed that the hydrochar is an environmentally friendly soil amendments for plant growth by slow release of nutrients and carbon sequestration. Hydrochar application to the soil may increase the soil's water-holding capacity but decreases the bulk density, although the water-holding capacity of hydrochar depends on the reaction temperature and particle size of the materials. Furthermore, the hydrochar may exert a positive effect on growth and abundance of different soil microbes. This paper not only summarizes the recent advances made in developing hydrochar as a soil amendment, it also discusses the challenges and limitations of hydrochar in a wider context.

**Keywords** Hydrothermal carbonization · Wet pyrolysis · Feedstock characteristics · Nutrient dynamics · Environmental sustainability

## Introduction

Soil plays a pivotal role in ensuring food security, ecological balance, and acting both as a sink and source of carbon dioxide in local and international contexts (Coomes and Miltner 2017). Deforestation, land use changes, excessive fertilizer and chemical use, unsustainable agriculture practices, and ground-water irrigation are the major causes of soil degradation throughout the world (Hobley et al. 2018). Potential alternatives are required to provide sustainable use of soil resources and reduce the worldwide problem of soil degradation. Despite the fact that applying char as a soil conditioner is not a new concept, there is much interest in using char for soil nutrient enrichment and ecological restoration through sequestering carbon (Farooque et al. 2020; Sigua et al. 2016). Patches of nutrient-rich soils along with cultural artifacts observed throughout the Amazon forest in South America is termed as Amazonian Dark Earth and locally called as terra preta (Bento et al. 2020; Glaser et al. 2001). Recent evidences and research proposed that the ancient deposition of volcanic ashes along with natural organic materials accretion may be principally responsible for the formation of this soil followed by traditional soil management practices by the tribes (Woods and McCann 1999). The Amazonian Dark Earth is very fertile due to the presence of stable carbonized materials, which maintain the soil's productivity (Lehmann 2009).

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In addition, scientists inspired by the nature of anthropogenic organic matter soil have subsequently considered biochar in land management practices to reduce global warming's impact on agriculture (Semida et al. 2019; Shen et al. 2020). Biochar is nothing but a carbonaceous solid material produced through thermal decomposition of biomass in an oxygen-limited environment (El-Naggar et al. 2018). Beyond versatile environmental applications such as energy production, carbon sequestration, agriculture, organic waste management, wastewater treatment, and bio-refinery, the biochar has received increasing attention in the last two decades because it is an efficient soil amendment (Panwar et al. 2019). It improves soil's physical, chemical, and biological properties, soil fertility, and crop production capacity. Biochar has the capacity to immobilize potentially toxic elements in soil as well as sequester carbon for more than 1000 years (El-Naggar et al. 2020; Hunt et al. 2010). Biochar therefore functions for a long time in the soil and has the ability to hold water, supply available plant nutrients, and provide an ideal environment for microbial activities.

However, the performance of biochar depends on certain characteristics of feed stock materials and the process conditions (Atkinson et al. 2010). Common and natural raw feedstocks are usually utilized for biochar production such as organic wastes, plant residues, wood chip, livestock manure, etc. (Ding et al. 2016). The common mechanisms for biochar production are fast pyrolysis, slow pyrolysis, and gasification, resulting in, respectively, bio-oil, solid biochar, and syngas, which are the primary by-products (Igalavithana et al. 2017). The physicochemical characteristics of biochar mostly rely on pyrolysis temperature. Generally, biochar production requires energy to dry the feedstock while the carbonization process raises the temperature to 300–650 °C in the absence of oxygen (Kambo and Dutta 2015). Moreover, biochar production demands harmful gas (CO, $CH_4$, and PAHs) management and control techniques (Meyer et al. 2011).

Wet biomass produced from the agro-industry and municipalities is a major concern globally due to ever-increasing stock and its potential to add extra greenhouse gases (GHGs) to the atmosphere while composting. Moreover, wet waste organic products typically require a large amount of energy to evaporate moisture and transform into biochar. In order to overcome these problems, hydrothermal carbonization (HTC) has recently got the attention of the scientific community because of its advantages over other widely applied thermochemical biomass conversion techniques including pyrolysis, torrefaction, and gasification (Peng et al. 2017). The HTC process, a simple form of wet pyrolysis where carbonization occurs under water in a very mild environment (180–250 °C), deals with wet biomass in an energy-efficient way and successfully converts wet biomass into lignite-like carbonaceous materials called "hydrochar" (Funke and Ziegler 2010; Breulmann et al. 2017a). In addition, HTC could conduct without pre-drying treatment and is cost-efficiency technology comparing with other thermal techniques (Peng et al. 2017). Therefore, HTC technology has recently got the scientific attention.

The hydrochar produced from different types of raw materials, like pig manure (Song et al. 2017), sweet grass and herbs (Röhrdanz et al. 2016), forest waste (Belda et al. 2016), beetroot chips (Bargmann et al. 2014), sewage sludge (Breulmann et al. 2017b), and giant miscanthus (Subedi et al. 2015), has been applied as soil amendments in recent times. The production methods, feedstock characteristics, and different applications of hydrochar have been reviewed by several authors (Kambo and Dutta 2015; Fang et al. 2018; Wang et al. 2018). However, no such extensive review has been published on hydrochar functioning as a soil amendment. Consequently, this paper seeks to critically review the current state of knowledge on hydrochar application to agricultural soils. We mainly focus on the state-of-the-art interpretation and identification of gaps in the scientific knowledge on the broad-spectrum effects of hydrochar on soil's properties and fertility. Moreover, the complex nature of hydrochar-based soil amendments is also discussed in this paper, followed by observations that may indicate and recommend future research directions or even offer a new conceptual framework.

## Hydrochars and their properties

### Hydrochar production process

The comparison of thermochemical transformations of biomass into different valuable products has been described in Table 1. Among the all thermochemical conversion process, the hydrochar production through HTC process is a simple one and requires no sophisticated technology. Several informative hydrochar articles have extensively described the production process, possible chemical reactions, fate of major constituents in the biomass, and its application (Funke and Ziegler 2010; Libra et al. 2011). Schematic diagram of HTC autoclave system is shown in Fig. 1 (Ma et al. 2019). The whole conversion of the waste materials occurs in a closed reactor. It is done by using temperature ranging from 180 to 250 °C with a pre-determined reaction time and feedstock ratio. No extra pressure is needed for the HTC process except autogenous pressure (approximately 2–6 MPa) of water in the inner chamber. Three types of HTC products are distributed in three phases (Libra et al. 2011): gas phase (5% wt), liquid phase (5 to 35% wt), and solid phase with a mainly coal-like substance termed "hydrochar" (50 to 80% wt).

Morphologically and physicochemically, hydrochar differs significantly from biochar, and these distinctions have already been discussed by several informative articles (Kambo and Dutta 2015; Fang et al. 2018). Biochar is produced at a higher

**Table 1** Comparison of thermochemical transformations of biomass (after Doyle et al. 2016)

| Treatment | Feed | Conditions | Main products |
|---|---|---|---|
| HTC | Wet/dry | 180–250 °C, autogenous pressure | Hydrochar, process water containing sugar and sugar derivatives, organic acids. |
| Pyrolysis (moderate) | Dry | 450–550 °C, absence of air | Biochar (40–70%), bio-oil, gas |
| Torrefaction | Dry | 280–350 °C, absence of air | Solid, torrefied biomass, gas |
| Gasification | Dry | > 800 °C, limited oxygen supply ($O_2$ or $H_2O$) | Solid (5–10%), syngas |

temperature than hydrochar and usually has a larger surface area and porosity (Sun et al. 2014; Inyang et al. 2010) and it has been clearly observed in the Fig. 2 (Abel et al. 2013; Fang et al. 2018). Hydrochar has lower carbon content due to lower dehydration during HTC process which makes it less stable in the soil (Gao et al. 2016; Fornes et al. 2015). Although the stability of hydrochar in soil depends on the reaction severity of process parameters especially on reaction temperature during HTC process (Wang et al. 2018), there is also less ash in hydrochar than in biochar (Abel et al. 2013). The ash content during HTC entered into the liquid phase but biochar retained all the ashes on the feedstocks. Hydrochar is acidic in nature and able to reduce the pH of highly alkaline soil (Fang et al. 2018).

## Reaction mechanisms during hydrochar production

HTC is a simple, benign, and eco-friendly process for converting wet biomass to char but reaction mechanisms during the process are still not completely understood, but this procedure is known to be complex. It is an exothermic process and completely depends on the feedstock characteristics, temperature, and reaction time and to some extent the heating rate (Abel et al. 2013; Eibisch et al. 2015a; Röhrdanz et al. 2016). Wiedner et al. (2013) showed that the chemical composition of hydrochar is more influenced by temperature than feedstock properties (Table 2). Typically, plant biomass comprises three types of biopolymers: cellulose, hemicellulose, and lignin. Of these, cellulose and hemicellulose are hydrolyzed or partly de-polymerized in the HTC process under a closed system in the presence of water at a moderate temperature (200 °C) and autogenous pressure (De Mena et al. 2016). Therefore, hydrolysis is the main mechanism that initiates the biomass degradation throughout the HTC process and water acts as a catalyst and curtails the activation energy. Moreover, water helps produce circulation by transferring organic fractions out of the biomass matrix during HTC (Funke and Ziegler 2010). For this reason, cellulose, hemicellulose, and lignin become less stable and are easily degraded within the mild temperature of the HTC process. Even lignin, which is a very complex, stable polymer and requires a temperature of 180–700 °C to degenerate during pyrolysis, can be broken down within 180–220 °C in the HTC process (Libra et al. 2011).

The hydrochar formation pathway from lignocellulosic biomass has been depicted in Fig. 3. In the HTC process,

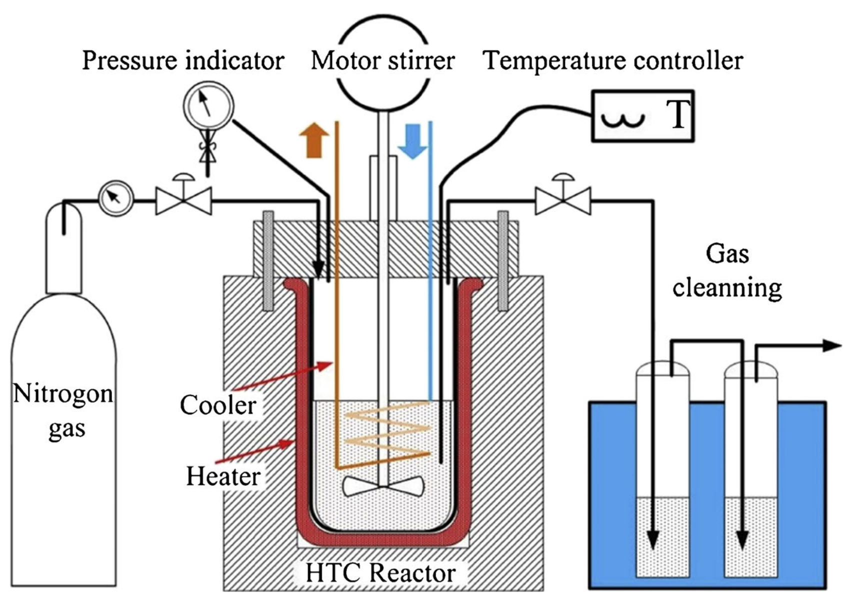


**Fig. 1** Schematic diagram of HTC autoclave system (adopted from Ma et al. 2019)

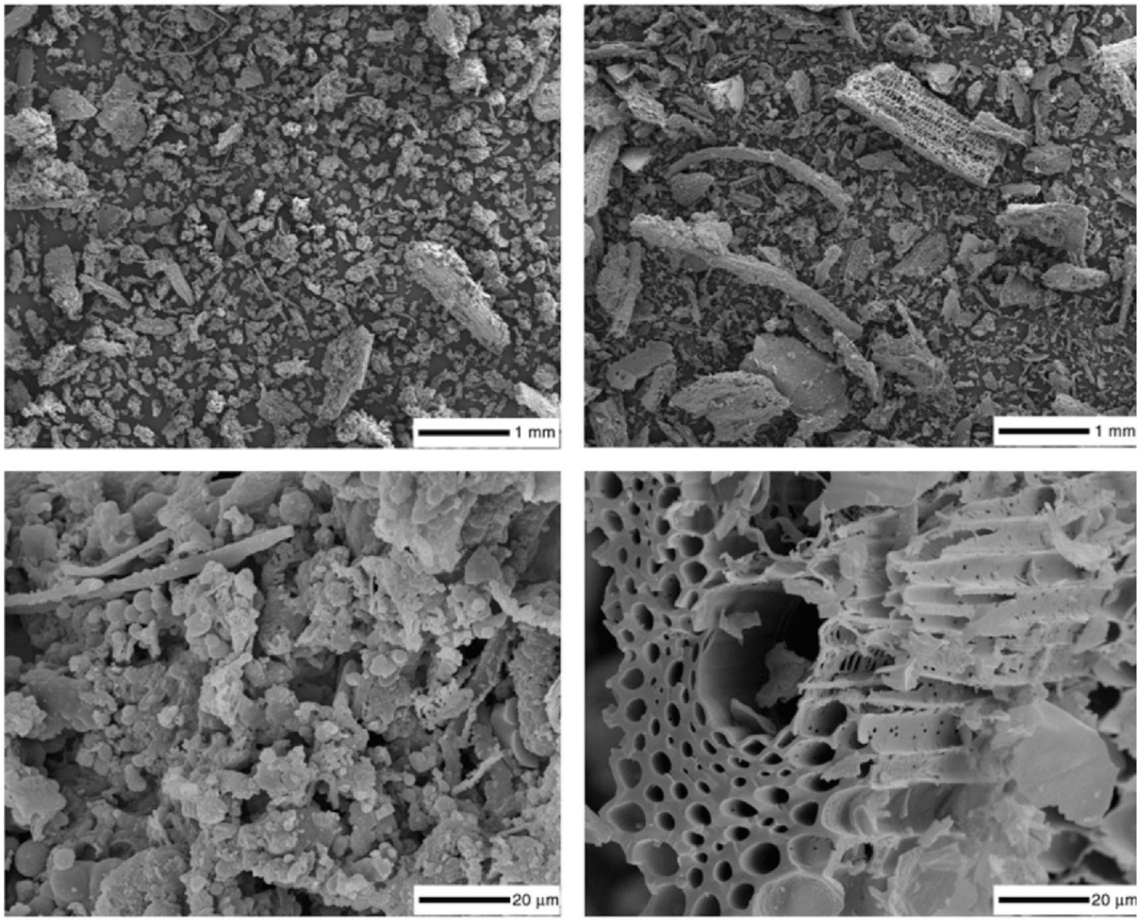


**Fig. 2** Electron-microscopic images comparing biochar and hydrochar. Left: hydrochar (feedstock maize silage); right: biochar (feedstock maize; upper images: 20×; lower images: 1000× magnified) (Abel et al. 2013; Fang et al. 2018)

temperature determines the char's porosity and there is a close relationship between porosity and surface area (Kambo and Dutta 2015). Oxygen and carbon atoms are eliminated from the biomass through dehydration and decarboxylation reactions and $H_2O$ and $CO_2$ are formed. Initially, all the soluble fractions or ions come into liquid phase, react, and form different types of unknown organic complexes. Subsequently, with prolonged time and temperature, these sugar molecules are turned into brownish carbonaceous hydrochar. Hydrochar closely resembles coal in that both go through identical production pathways. Coal formation involves humification under a mild environment (temperatures approximately 170–275 °C for anthracite coal) and hydrochar in the HTC process involves aromatization and condensation reaction mechanisms (Libra et al. 2011; Straka and Sýkorová 2018). Furthermore, during HTC process, some very reactive fragments and unsaturated compounds are polymerized by condensation reactions and precipitate on the surface of the hydrochar (Funke and Ziegler 2010). The reactive fragments also reduce the porosity of hydrochar by blocking the pores of initially produced porous hydrochar (Abel et al. 2013).

## Hydrochar's effects on soil properties

According to published papers in this subject, hydrochar is a promising and appropriate soil amendment due to its versatile chemical structure and morphology. These aspects are explained in more detail in the following sections.

### Soil's physical properties

One of the main soil properties after char treatments in general is increased crop production and prevention of soil degradation by enhancing total soil porosity, water-holding capacity (WHC), and the formation and stability of soil aggregates. One study by Abel et al. (2013) found the increased WHC of sandy and sandy loam soil at 2.5 wt% rate of maize silage hydrochar application. This study also discovered that the further addition of hydrochar after 2.5 wt% did not significantly increase the WHC of the studied soils with high organic matter content. A growing media prepared with mixing peat and biosolid hydrochar had increased the WHC by 21% with respect to peat alone (Álvarez et al. 2017). In another study, the

**Table 2** Physicochemical analysis of feedstocks and their corresponding hydrochar properties followed by HTC

| Feedstock | pH | C | N | P | K | Ash | H/C | O/C | Surface area ($m^2/g$) | HTC conditions | | pH | C | N | P | K | Ash | H/C | O/C | Surface area ($m^2/g$) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | g $kg^{-1}$ | | | | | | | | Temperature (°C) | Time (h) | | g $kg^{-1}$ | | | | | | | | |
| Watermelon peel | 4.8 | 411.8 | 16.3 | 8.3 | 28.9 | 91.7 | 1.91 | 0.75 | - | 190 | 6 | 4.6 | 588.0 | 22.2 | 9.5 | 14.7 | 62.4 | 1.20 | 0.34 | - | Chen et al. (2017) |
| Digestates | 9.9 | 392.0 | 34.1 | - | 42.5 | 237.0 | 1.50 | 0.58 | - | 180 | 8 | 7.6 | 446.0 | 18.2 | - | 2.5 | 148.0 | 1.50 | 0.54 | 6.4 | Eibisch et al. (2013) |
| Grass | 6.9 | 439.0 | 38.7 | - | 30.1 | 122.0 | 1.60 | 0.58 | - | 180 | 8 | 5.1 | 474.0 | 22.8 | - | 2.5 | 145.0 | 1.40 | 0.50 | 5.5 | Eibisch et al. (2013) |
| Straw | 7.2 | 452.0 | 6.3 | - | 20.4 | 69.0 | 1.60 | 0.62 | - | 180 | 8 | 5.7 | 496.0 | 4.3 | - | 0.4 | 26.0 | 1.50 | 0.55 | 3.7 | Eibisch et al. (2013) |
| Wood chips | 5.6 | 488.0 | 1.8 | - | 0.7 | 7.0 | 1.50 | 0.61 | - | 180 | 8 | 4.0 | 516.0 | 1.7 | - | 0.40 | 19.0 | 1.40 | 0.51 | 1.9 | Eibisch et al. (2013) |
| Sludge | 6.3 | 513.0 | 4.2 | 23.3 | 4.2 | 287.0 | 1.60 | 0.99 | | 180 | 4 | 5.8 | 586.0 | 3.3 | 27.5 | 5.1 | 33.5 | 1.50 | 0.70 | | Breulmann et al. (2017a) |
| Miscanthus straw | 6.8 | 479.0 | 1.2 | - | - | 20.4 | 1.60 | 0.71 | - | 200 | 2 | 5.1 | 504.7 | 1.9 | 0.01 | - | 31.3 | 1.30 | 0.55 | 3.5 | Schimmelpfennig et al. (2014) |
| Miscanthus straw | - | 479.0 | 1.2 | - | - | 16.0 | 1.40 | 0.70 | - | 240 | 8 | - | 664.0 | 2.4 | - | - | 21.0 | 0.80 | 0.50 | - | Schimmelpfennig et al. 2017) |
| Digestates | - | 419.0 | 15.7 | 12.8 | 28.8 | 119.0 | 0.14 | 0.87 | 8.6 | 200 | 6 | 6.2 | 538.0 | 25.9 | 12.3 | 9.8 | 103.0 | 0.10 | 0.46 | 1.3 | Gronwald et al. (2015) |
| Digestates | - | 419.0 | 15.7 | 12.8 | 28.8 | 119.0 | 0.14 | 0.87 | 8.6 | 250 | 6 | 5.7 | 618.0 | 29.8 | 15.6 | 14.1 | 136.0 | 0.08 | 0.29 | 2.8 | Gronwald et al. (2015) |
| Miscanthus | - | 456.0 | < 10 | 0.9 | 5.3 | 29.0 | 0.13 | 0.86 | 1.0 | 200 | 6 | 4.6 | 580.0 | < 10 | 1.3 | 2.7 | 39.0 | 0.10 | 0.46 | 5.2 | Gronwald et al. (2015) |
| Miscanthus | - | 456.0 | < 10 | 0.9 | 5.3 | 29.0 | 0.13 | 0.86 | 1.0 | 250 | 6 | 4.2 | 690.0 | < 10 | 1.7 | 3.0 | 45.0 | 0.08 | 0.27 | 5.8 | Gronwald et al. (2015) |
| Woodchips | - | 486.0 | < 10 | 0.7 | 2.7 | 42.0 | 0.12 | 0.71 | 1.6 | 200 | 6 | 4.6 | 597.0 | 10.7 | 0.8 | 2.5 | 50.0 | 0.10 | 0.40 | 10.0 | Gronwald et al. 2015) |
| Woodchips | - | 486.0 | < 10 | 0.7 | 2.7 | 42.0 | 0.12 | 0.71 | 1.6 | 250 | 6 | 4.8 | 677.0 | 12.2 | 1.1 | 2.1 | 54.0 | 0.08 | 0.27 | 3.5 | Gronwald et al. (2015) |
| Solid digestates | - | 331.0 | 47.0 | 24.5 | 6.3 | 353.0 | - | - | - | 150 | 1 | - | 355.0 | 39.0 | 24.2 | 4.8 | 382.0 | - | - | - | Løes et al. (2017) |
| Solid digestates | - | 331.0 | 47.0 | 24.5 | 6.3 | 353.0 | - | - | - | 200 | 1 | - | 354.0 | 30.0 | 27.8 | 4.5 | 440.0 | - | - | - | Løes et al. (2017) |
| Seaweed | - | 352.0 | 34.1 | 1.7 | 30.4 | 232.0 | - | - | - | 150 | 1 | - | 437.0 | 29.0 | 3.6 | 23.6 | 250.0 | - | - | - | Løes et al. (2017) |
| Seaweed | - | 352.0 | 34.1 | 1.7 | 30.4 | 232.0 | - | - | - | 200 | 1 | - | 429.0 | 29.0 | 3.4 | 25.2 | 253.0 | - | - | - | Løes et al. (2017) |
| Miscanthus | 6.8 | 479.4 | 1.2 | < 0.1 | < 0.1 | - | - | - | 1.1 | 200 | 2 | 5.2 | 504.7 | 1.9 | < 0.1 | < 0.1 | - | - | - | 3.5 | Rex et al. (2015) |
| Orange peel | 4.64 | 441.0 | 9.8 | - | 12.79 | 45.8 | - | - | 0.7 | 200 | 8 | 4.7 | 662.0 | 9.8 | 0.2 | 12.8 | 63.4 | 0.94 | 0.47 | 7.1 | Kalderis et al. (2019) |
| Digestate | 7.6 | 420 | 15.7 | - | - | - | 1.53 | 0.65 | 8.6 | 250 | 6 | 6.4 | 622.0 | 29.8 | - | - | - | 0.91 | 0.22 | 2.8 | Eibisch et al. (2015b) |
| Miscanthus | 5.6 | 460 | 5.2 | - | - | - | 1.48 | 0.65 | 1.0 | 250 | 6 | 4.9 | 690.0 | 11.8 | - | - | - | 0.86 | 0.20 | 5.8 | Eibisch et al. (2015b) |
| Woodchips | 4.8 | 490 | 7.8 | - | - | - | 1.36 | 0.63 | 1.6 | 250 | 6 | 5.3 | 680.0 | 12.22 | - | - | - | 0.89 | 0.20 | 3.5 | Eibisch et al. (2015b) |
| Digestate | 7.6 | 420 | 15.7 | - | - | - | 1.53 | 0.65 | 8.6 | 200 | 6 | 6.3 | 540.0 | 25.9 | - | - | - | 1.15 | 0.34 | 13.0 | Eibisch et al. (2015b) |
| Miscanthus | 5.6 | 460 | 5.2 | - | - | - | 1.48 | 0.65 | 1.0 | 200 | 6 | 4.7 | 580.0 | 6.7 | - | - | - | 1.09 | 0.35 | 5.2 | Eibisch et al. (2015b) |
| Woodchips | 4.8 | 490 | 7.8 | - | - | - | 1.36 | 0.63 | 1.6 | 200 | 6 | 5.0 | 600.0 | 10.7 | - | - | - | 1.06 | 0.40 | 10.0 | Eibisch et al. (2015b) |

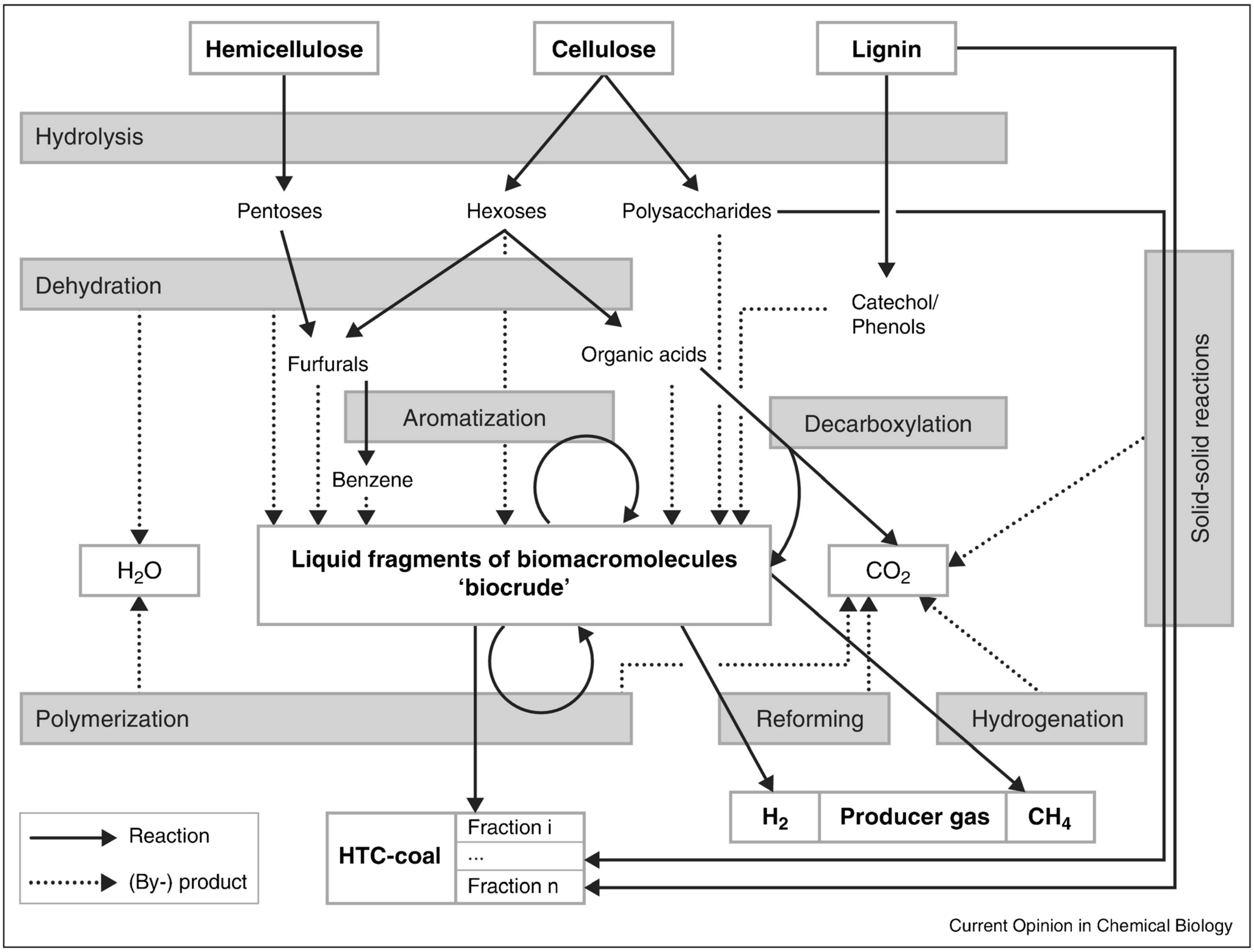


**Fig. 3** Mechanism pathways for the formation of hydrochar from lignocellulosic biomass (Kruse et al. 2013)

hydrochar from forest waste showed less easily available water when mixed with soil (Belda et al. 2016). However, the study by Kalderis et al. (2019) observed an unaffected WHC at the 5% rate of orange peel hydrochar application. Röhrdanz et al. (2016) wrote that the WHC of hydrochars produced biomass from landscape management fell with increased reaction severity in terms of reaction time and temperature during hydrochar production. The reaction severity induced only C content but not higher WHC. Consequently, the authors suggested that employing the mild carbonization process (mainly temperature at 180 °C) to produce hydrochar will obtain the highest WHC values when applied in sandy soil. Thus, HTC products are not identical because the process parameters and feedstocks influence the final properties of hydrochar (Eibisch et al. 2015a). The study by Eibisch et al. (2015a) also postulated that hydrochar produced from small-sized particles of feedstock and carbonized at low temperature (usually 180 °C) was suitable for retaining water capacity in a loamy sand soil. Moreover, the respiration rates of coarse and fine textured soil have increased due to the presence of C in corn silage hydrochar (Malghani et al. 2015).

The application of maize silage hydrochar on sandy soil decreases the soil's bulk density as reported by Abel et al. (2013). This study also explained that porosity along with spherical shapes and structural deformability of the hydrochar particles may regulate the bulk density. Apart from this, the coarseness index (CI) that describes the particle size distribution of soils or chars may in fact influence the bulk density of soil-hydrochar mixer. The 30% (*v*/*v*) of dilution hydrochar with soil showed the highest CI value with lower bulk density than the soil. Soil heaviness and compactness are responsible for its high bulk density than the hydrochar. As a result, by adding light hydrochars to the soil does not drastically reduce the bulk density of soil-char mixers. However, Eibisch et al. (2015a) showed that an increase of total porosity may provoke a decline in the bulk density. In the same study, the authors reported the increased water repellency of hydrochar due to fungal colonization. In both the greenhouse experiment and soil incubation study of plant growth by applying spent brewer's grain hydrochar, George et al. (2012) observed the positive effects of hydrochar on water stable macroaggregates. These macroaggregates were formed due to the activities of plant root with organic matter and hydrochar particles in the soil.

## Soil's chemical properties

The soil pH has an enormous effect on ion solubility in soil which regulates microbial and plant growth (Neina 2019). Generally, hydrochar is acidic in nature as described in Table 2 (Libra et al. 2011; Fang et al. 2018; Kalderis et al. 2019) and it becomes more acidic with a gradual increment in reaction temperatures (Saha et al. 2019). Saha et al. (2019) also described that the acidic pH of hydrochar is mainly responsible for forming organic acids on the hydrochar surface; these organic acids (acetic, lactic, furanic, formic) act as catalysts for further hydrolysis reaction of untreated biomass (Jain et al. 2016) and continue to decrease pH with reaction temperature. George et al. (2012) noted a decline in soil pH when applying 10% spent brewer's grain hydrochar rather than the 5% rate; yet, 10% leachate of hydrochar mixed with soil did not alter the soil pH. This may have happened due to the higher $OH^{-}$ ions on the leachate that cannot compromise with the soil pH to reduce acidic pH. Ren et al. (2017) detected a fall in soil pH after application of sewage sludge (SS) hydrochar although the hydrochar's pH was lower than the soil pH. Such a decrement of pH might be triggered by the oxidation of hydrochar surface with the time taken to create more carboxylic functional groups (Melo et al. 2017). In contrast, Busch et al. (2013) found that the pH values of soil mixed with hydrochar were higher at the addition rate of 7% (*v*/*v*) than the soil pH (5.8) and hydrochar pH (3.9). Mixing soil (pH 8.7) with forest waste hydrochar (pH 8.2) accelerated in pH (8.7) at the hydrochar application rate of 30%. However, at the rate of 15%, the mixing effect of pH (8.2) was not observed (Belda et al. 2016).

Electrical conductivity (EC) generally determines the level of soil salinization. The increased occurrence of salt in soil interrupts the balance of water and nutrients due to the low osmotic potential in the soil solution which is detrimental to plants (Lech et al. 2016). The decline in soil salinity means a decrease in EC values which may benefit plant growth (Ren et al. 2017). Belda et al. (2016) reported rising EC values of 25, 31, and 40 mS $m^{-1}$ through the application of hydrochar at the rate of 5%, 15%, and 30%, respectively, while the EC value of soil was 13 mS $m^{-1}$. The higher organic matter content in hydrochar than the soil is the main factor responsible for the increase in the EC for soil-hydrochar-mixer. The analysis by Belda et al. (2016) found EC values of raw sewage sludge 1441 μS $cm^{-1}$, and after it was processed by HTC, the EC value decreased to 100–300 μS $cm^{-1}$ (sewage sludge hydrochars). Under ambient temperatures and reaction time during HTC, the decomposition of SS released almost dissolved salts to the liquid phase with very little left in the hydrochars. The end result was very low EC values. However, with the addition of sewage sludge hydrochar to soil, soil EC values (521 μS $cm^{-1}$) decreased to the 403–535 μS $cm^{-1}$ range. This phenomenon may have been observed due to the low EC values of hydrochars along with varying process temperatures and reaction times. Busch et al. (2013) also delineated the effects of composted hydrochars in soil mixtures (10 and 30 Mg $ha^{-1}$) and reported an increase in conductivity up to 2767 μS $cm^{-1}$. These authors also observed unchanging effects on EC when the addition of fresh hydrochar to soil was taken into account. Moreover, hydrochar application may decrease the cation exchange capacity (CEC) and elemental O/C ratio in soil (Röhrdanz et al. 2016).

## Soil's biological properties

Microorganisms are important for soil health and play vital roles in soil nutrient dynamics (Tinker 1984). The structure and function of biological organisms are complex in soil due to the presence of diversified dwellers like protozoa, arthropods, fungi, bacteria, and other invertebrates. Fixation of atmospheric N, recycling of carbon, synthesizing enzymes and nutrients, and suppression of soil-borne pathogens are major roles usually played by soil microorganisms (Altieri 1999). Hydrochar has a potential role in soil amelioration since it delivers essential nutrients and total organic carbons to soil (Busch and Glaser 2015). The potential impact of hydrochar on soil microbial community is still rarely reported in the literature. However, a few analyses documented the positive effects of hydrochar on growth and abundance of different soil microbes (Rillig et al. 2010; Álvarez et al. 2017; Ren et al. 2017). Conversely, Andert and Mumme (2015) reported that the application of hydrochar reduced the Acidobacteria 5- to 6-fold more than the control, whereas the abundance of Firmicutes was less than one-third compared with the control. The abundance of Bacteroidetes and Proteobacteria, however, increased 2.4 and 1.6–1.7 times, respectively, more than the control. The shift in this microbial community is expected due to the easily degradable carbon and low pH of hydrochar. Reibe et al. (2015a) investigated the effects of maize silage methanogenic fermented hydrochar on the *Protaphorura fimata* and spring wheat and found firstly, a declining amount of *P. fimata*; and secondly, increased shoot biomass of wheat with rising amounts of fermented hydrochar in a laboratory scenario. This may have happened due to chemical effects of phenolic and aromatic substance present in the hydrochar, which ultimately reduced the grazing pressure on root and promoted the shoot biomass. It has been found from one recent study that the abundance of ectomycorrhizal fungi in association with seedling growth was higher with hydrochar application produced from paper mill biosludge than the control (Eskandari et al. 2019). In contrast, the hydrochar made from spent brewer's yeast detected a negative effect of hydrochar on the abundance of arbuscular mycorrhiza fungal (AM-fungi) root colonization at the rate of 5% and 10% hydrochar application. However, root nodulation markedly increased by 10% more hydrochar being added (George et al. 2012). The probable causes of this dual behavior may be the reduced pH level in soil that causes necrosis on the plant leaf tip by application of more hydrochar (10%). The authors also assumed that not only the pH but also the physical and chemical properties, nutrients, phytotoxicity of hydrochar due to the presence of organic acids and phenols, and nutrient immobilizations may be responsible for these negative effects. Nonetheless, Melo et al. (2017) noted a similar result regarding the decline in soil pH after SS hydrochar was applied at a higher rate (4%). The authors did not find any negative effects of SS hydrochar on earthworms against four concentrations (0.5%, 1%, 2%, and 4%). These results were explained by the available trace elements of SS hydrochar that are not toxic to earthworms. Salem et al. (2013) found the increased plant shoot and root biomass in association with earthworms even at high dosages of beet root chips hydrochar application but effects on earthworms were not observed at the control (without hydrochar) and the low hydrochar addition to the sandy loam soil. Earthworms consume carbonized particles from chars and excrete them as casts which are full of nutrients (Weyers and Spokas 2011). In this way, earthworms neutralized phytotoxic substances of hydrochars through physiological processes which made the nutrients in plant available form (Busch et al. 2012).

## Hydrochar's effects on plant growth and development

Soil nutrient deficiency on a global scale is becoming an increasingly important problem and supplementary fertilization has been intensified in many agricultural activities. Indeed, the application of composts, mulches, manure, and similar organic soil amendments enhance soil fertility. Depending on climatic conditions and land use, organic matter from these materials can be mineralized rapidly, and only a small portion of the applied organic compounds will be stabilized in soil in the long term (Agegnehu et al. 2017). Hydrochar, as a material containing more stable carbon compounds, modifies the chemical environment of soil and promotes nutrient acquisition and microbial activity (Busch and Glaser 2015; Fang et al. 2018). Generally, hydrochar is acidic, and thus, applications of hydrochar in soils lower soil alkalinity (Ren et al. 2017). Elsewhere, forest waste hydrochar proved to be slightly alkaline, rich in nutrients with N, Ca, S, and Fe than the biochars, and had high microbial respiration capacity (Fornes et al. 2015). Several authors proposed the processed water of hydrochars as a good source of liquid fertilizer which is enriched with nitrogen and potassium and free of heavy metals (Sun et al. 2013). Hydrochar does not immobilize N but it can be used as a soil amendment when slow release of N fertilizer is required (Busch and Glaser 2015; Fornes et al. 2015). Fine-grained hydrochar is a short-term source of $PO_4$, K, and $NH_4^+$ in soil irrespective of soil types (de Jager et al. 2019). Recently, one study indicated the potential source of humic-like substances as plant growth promoters from HTC of bagasse biomass which promoted maize seed germination more effectively (Bento et al. 2020). The blends of hydrochar with fresh organic materials like animal manure or crop residues may increase nutrients' availability to the plant by reducing the effects of N immobilization (Bargmann et al. 2014). However, it seems that the application of hydrochar as a direct fertilizer wielded no influence on soil fertility. Nonetheless, the blending of biochar and hydrochar might improve soil fertility, mainly P and K contents (Novak et al. 2014). Meanwhile, more recent findings confirmed that the nutrient release from hydrochar depends on soil types (Melo et al. 2019) and hydrochar ratios (Bento et al. 2019).

It has been reported recently that potential N fertilization depends on hydrochar produced at a low temperature (Paneque et al. 2019). Generally, the temperature of the HTC process determines the type of nutrient availability. Higher temperature range in HTC reduced the release of macronutrients (N, P, K) and organic matter but increased the release of micronutrients, i.e., Cu and Zn (Løes et al. 2017; Song et al. 2017; Ro et al. 2016). The different nutrient contents in the liquid and solid phase of hydrochar prepared from woodchips, straw, grass cuttings, and digestate were examined and high concentrations of Ca, K, Mg, N, and Na in the liquid phase were detected. Yet, most of the elemental concentrations in hydrochars were depleted quickly, mostly K (Eibisch et al. 2013). Hydrochar produced from wood and maize increased the nodule dry matter of soybean and biological nitrogen fixation (BNF) to 1.8- and 1.2-fold than pyrochar, respectively, irrespective of all soil types (Scheifele et al. 2017). Authors also detected a positive relationship of available sulfur between nodule dry matter and BNF but a negative one with N content. Hydrochars provide more available sulfur than nitrogen to soil so there was a positive influence on nodulation.

Researchers are still in a dilemma about using hydrochar to promote plant growth despite laboratory experiments proving to be very encouraging (Table 3). Field application of hydrochar has been reported in some studies over the last decade (Rillig et al. 2010; George et al. 2012; Busch et al. 2013; Schimmelpfennig et al. 2014). Hydrochar application in soil totally inhibited germination when initiated at the addition rate of 2.5% (*v*/*v*) and later a higher addition rate (7.0%) than biochar in some cases (Busch et al. 2013). This curtailing of germination happened not only due to the effect of pH value but also the toxic substances that formed during hydrothermal

**Table 3** The effects of hydrochar amendment on plant growth and crop yield

| Hydrochar feedstocks | Plant | Production conditions | | Application rate | Soil type | Impact on soil properties | Crop response | References |
|---|---|---|---|---|---|---|---|---|
| | | Temperature (°C) | Time (h) | | | | | |
| Poplar | Oat | 200 | 2 | 0, 1, 2.5, and 5%. | Former sewage-field | Decreased nitrogen availability | Reduced biomass production | Wagner and Kaupenjohann (2014) |
| Maize | Soybean | 200 | 4 | 20 ton/ha | Arable soils | Hydrochars had no or only very slight pH effects | Increase biological nitrogen fixation capacity | Scheifele et al. (2017) |
| Maize treated with or without digestate | Spring wheat | 210 | 8 | - | Pot experiments | -- | Untreated hydrochar had negative effects on yield | Reibe et al. (2015b) |
| Miscanthus × giganteus | Grass | 200 | 2 | 1–45 kg/m$^2$ | Grass land | Nutrient concentrations enriched | Biomass growth was not affected | Schimmelpfennig et al. (2015) |
| Biosolids and organic urban waste | *Lolium perenne* | Biosolids: 190–200 Urban waste: 205–215 | 6 | 50% volume rate with peats | Peat lands | Increased water holding capacity more than 21% and porosity more than 19.8% | Biomass production increased up to 180% | Álvarez et al. (2017) |
| Maize silage | Spring wheat | 210 | 8 | 1, 2, and 4% | Pot experiments | Increased soil organic carbon | Shoot and root biomass of wheat were not significantly affected by any of the char amendments | Reibe et al. 2015a) |
| Maize silage | Poplar tree | 230 and 180 | 15 and 75 min | 30 t/ha | Field | Increased soil carbon and nitrogen | Stimulating plant growth. | Baronti et al. (2017) |
| Forest waste | Mastic and myrtle | - | - | 0, 10, 25, and 50% | Calcaric Arenosol | Caused nitrogen immobilization | Growth for both species was not affected but showed immobilization of nitrogen | Belda et al. (2016) |
| Miscanthus × giganteus | Lolium perenne | 200 | 2 | 14.5 t/ha | Haplic stagnosol | -Increased soil pH from 5.2 to 5.8<br>-Increased soil water-holding capacity by + 14% | Reduced biomass growth | Schimmelpfennig et al. (2014) |
| Beet-root chips and spent brewer's grains | Barley, leek, and phaseolus bean | 180–190 | 4, 8, and 12 | 30 ton/ha | Loamy sand | -Reduced concentration of mineral N in soil<br>- Increased soil pH<br>-Immobilize N in soils | Positive effect on biomass production | Bargmann et al. (2014) |
| Sewage sludge | *Lolium perenne* | 200, 260 | 0.5 and 2 | 5 and 25 ton/ha | Calcic Cambisol | -Low-temperature (200 °C) HTC product have N fertilization potential<br>-Increase nitrogen content | Hydrochar produced at low temperature have higher plant growth | Paneque et al. (2019) |
| Maize silage | Poplar | 230, 180 | 0.15 and 1.15 | 9.2 g/pot | Sandy soil, pot experiment | -Short-term source for N<br>-Char did not affect nitrogen use efficiency | Biomass allocation in different parts other than productivity | George et al. (2017) |

carbonization. Moreover, the toxic effect of fresh hydrochar on *Tradescantia* plants was more pronounced since fresh hydrochar contains more toxic and harmful compounds than aged hydrochar. Bargmann et al. (2014) confirmed that crop response to hydrochar application depended on crop species. It has also been observed that biomass production of phaseolus beans increased tremendously while the biomass growth of leek as reduced. In another study, Schimmelpfennig et al. (2014) observed severe growth reduction when incubation time lasted for a long time before sowing. Moreover, the severely inhibited germination of maize, lettuce, and tomato seeds was observed when the application of concentrated processed water from HTC of sugarcane bagasse and vinasse was employed (Fregolente et al. 2019).

The rate of hydrochar application influences biomass production, nutrient dynamics, and overall plant growth. Wagner and Kaupenjohann (2014) found that adding poplar hydrochar did severely compromise biomass production and reduced 50% of both fresh and dry matter. Consequently, it was not recommended as a soil amendment. According to this study, limited N (less than 1% found) was responsible for this negative synergy, while intensified microbial availability of hydrochar C led to N inadequacy. Besides, all other cations (e.g., P, K, Ca, Fe, Cu, Zn, Cd) except Mg and Mn were reduced with hydrochar percentages (1–5%). After implementing hydrochar as a soil amendment, beyond this, the yields decreased and the total N uptake reduced by 66%, followed by other nutrients by 61–74% except for Mn (41%) and Mg (49%). However, Pb was found in smaller amounts than its detection limit. A similar reduction in plant growth was documented by Belda et al. (2016) in their experiment involving forest waste hydrochar on mastic and myrtle growth. Conversely, the application of hydrochar produced from maize silage showed a considerable biomass increase in poplar species (Baronti et al. 2017). George et al. (2017) reported increased biomass productivity and N allocation when hydrochar was applied to poplar trees. They extracted 24% char derived nitrogen which was adsorbed by hydrochar-treated poplar trees. A positive effect of hydrochar application on shoot biomass of spring wheat was identified in the case of maize silage hydrochar (Reibe et al. 2015a. Sewage sludge hydrochar application augmented the total biomass production, while the application rate did not reveal any significant changes (Paneque et al. 2015). The N availability of hydrochar was identified as a significant factor in the growth of *Lolium perenne*, where P and K showed no correlation with growth parameters due to its limited availability in hydrochar. A similar observation was recorded when wood hydrochar and maize hydrochar were applied to soils (Baronti et al. 2017; Scheifele et al. 2017). A recent study showed that modified sewage sludge hydrochar with Mg-citrate and $H_2SO_4$ increased paddy soil N retention, which in turn increased N uptake in rice and subsequent yield (Chu et al. 2020).

The phytotoxic effect of hydrochar on plant growth was reported and this can be minimized by different detoxification strategies including physical (washing), chemical (oxidation by $H_2O_2$), and biological (composting) means (Melo et al. 2017). Some authors identified toxicity as existing either in liquid phase (George et al. 2012) or solid hydrochar (George et al. 2012; Chakrabarti et al. 2015). The liquid phase toxicity of hydrochar derives from the degradation products (mainly organic acids and phenolic compounds) of cellulose, hemicellulose, and lignin (Libra et al. 2011; George et al. 2012). All four samples of hydrochar are toxic to *Tradescantia* as described by Busch et al. (2013). The authors tried to minimize this toxic effect by co-composting hydrochar and found a significant reduction of micronuclei body. This reduction in toxicity was greater when hot water was used to wash the hydrochar. This study also noted the presence of HMF (hydroxy-methyl-furfural) which is one of the most suspicious substances for predicting toxicity. However, using water to wash hydrochar may decrease the total content of essential elements such as Ca, Mg, Mn, and Zn. This is because hydrochar contains a large amount of labile metals (Al-Wabel et al. 2019). Besides, this study also found the presence of handsome amount of polyaromatic hydrocarbons (PAHs) on hydrochars than biochars that may also be responsible for the toxicity that retards lettuce germination. Apart from this, recent findings demonstrated that the phytotoxic effect on germination and growth may be reduced by co-composting of hydrochar in a fixing ratio of 50:50 than untreated freshly mixed substrates (Roehrdanz et al. 2019). The co-composting of hydrochar increased the possible microbial degradation of harmful substances on the hydrochar's surface and immobilized the mineral N. Thus, plant growth increased. Pretreatment by combining sawdust hydrochar with microbial fermentation before soil application has been reported by Yu et al. (2019); it helped reduce phytotoxicity and increase porosity, but also increased nutrients and rice yield. This study explained that the microbial aged hydrochar increased rice yield by 17.13% compared with 22.29% for the control. This positive outcome for rice grain yield percentage may be due to much reduced toxicity and increased release of nutrients by microbial aging. However, the synergistic effect of both microbial aging followed by washing resulted in a large rice yield through better productivity. Another recent report by Bahcivanji et al. (2020) suggested that hydrochar followed by pyrolysis may eliminate phytotoxicity. The rice husk hydrochar's toxicity due to the furfural and phenols was significantly abated through the treatment of acetone and water (Chakrabarti et al. 2015). A recent study by Puccini et al. (2018) reported the necessity of post-treatments of hydrochar before application as peat substitute in potting mix, due to considerable phytotoxic effects on lettuce seed germination and radicle length as described in Fig. 4.

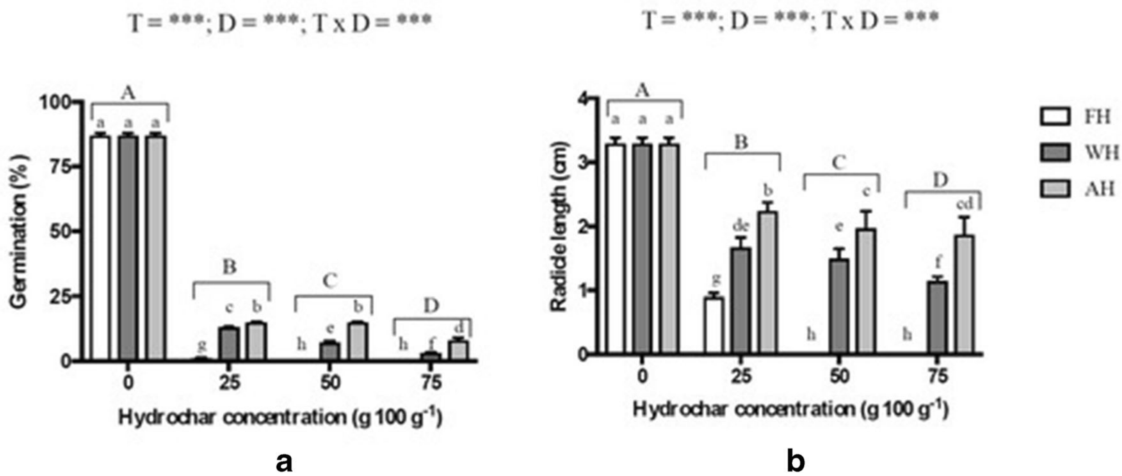


**Fig. 4** Effect of treatment (washed hydrochar, WH, and aged hydrochar, AH), hydrochar doses (0%, 5%, 10%, 15%, and 20%, wt%) and their interaction on lettuce seeds: **a** seed germination; **b** radicle length

## Carbon sequestration

Hydrochar-amended substrates can help mitigate the effects of climate change with carbon sequestration as part of the normal reforestation by replacing peat soil as well as fertilizer (Eskandari et al. 2019). Hydrochar is partially carbonized and therefore less stable and decomposes at a faster rate than biochar. The presence of less polyaromatic C and dominance of aliphatic compounds in hydrochar accelerated microbial degradation and made hydrochar less stable in soil in comparison with biochar (Fuertes et al. 2010; Hu et al. 2010). However, de Resende et al. (2018) recently revealed that the existence of PAHs in biochar-amended soil gradually decreased over time. It has also been reported that there is no risk of PAHs accumulating in soil after biochar has been applied for 6 years. Malghani et al. (2015) reported 19 years half-life of corn silage hydrochar in soil. They also concluded that hydrochar protects soil C from decomposition since hydrochar C gradually stabilizes after initially rapid decomposition. A high degradability of hydrochars in soil corresponds with a large amount of hydrophilic (hydroxyl, carbonyl, and carboxyl) functional groups, low C/N ratio, and a low lignin content of the raw material (Eibisch et al. 2013). In one study by Schulze et al. (2016), the authors explained that there is no relationship between hydrochar stability and lignin content; instead, it depends on repeated recirculation of processed liquor and application of temperature ranging from 210 to 230 °C. High reaction temperature and more recirculation of processed water led to higher stability of hydrochar by increasing the C content. Gajić et al. 2012 explained the potential of hydrochar to restore as well as preserve the soil's organic carbon but was not suitable for a long-term C sequestration process.

Moreover, hydrochar along with fertilizer inputs and high moisture give rise to high $CO_2$ emissions originating from soil (Andert and Mumme 2015; Belda et al. 2016). Kammann et al. (2012) pointed out that hydrochar can generate noticeably higher GHG emissions ($CO_2$, $N_2O$, $CH_4$) than biochar after N fertilization. Conversely, Doyle et al. (2016) found that hydrochar can reduce GHG emissions by avoiding the composting of fresh biowaste. Hydrochar application in soil has a positive effect on soil aggregation and shows good potential for carbon sequestration at least on the decade-based scale (George et al. 2012; Naisse et al. 2015). Moreover, the washing of hydrochar before its application to the soil may reduce biological decomposition. It can do this by eliminating superficially adsorbed labile components that might increase the C sequestration potential for a long time (Breulmann et al. 2017b).

## Environmental risks and remediation of pollutants

Hydrochar is apparently effective for sorption of polar and non-polar organic pollutants from the soil due to the presence of both amorphous alkyl and aryl C moieties (Han et al. 2016). Peng et al. (2017) studied HTC as an effective pretreatment technology for converting municipal solid waste hydrochar. They indicated that the significant reduction of heavy metals and PAHs in municipal sewage waste could be achieved by HTC. These authors also reported that Pb, As, Ni, Cu, and polycyclic aromatic hydrocarbons (PAHs) may accumulate in hydrochar when a high temperature range is used in production processes. Moreover, sewage sludge hydrochar application in soil increased both total and oxidizable fractions of heavy metals that later transformed into acid soluble fractions (Yue et al. 2017). Hydrochar may also contain several other chemical substances, for instance organic acids, phenols, and hydroxy-methyl-furfural (Bargmann et al. 2013; Wagner and Kaupenjohann 2014); all these can possibly act as phytotoxins and genotoxins (Busch et al. 2013). Heavy metals generally accumulate in the hydrochar during the carbonization process and have less chance of bioaccumulation into biomass (Schimmelpfennig et al. 2015). Ren et al. (2017) stated that hydrochar application in contaminated soil immobilized the Cd phyto-availability to plants. Flora et al. (2013) recommended washed hydrochar instead of unwashed hydrochar as soil adsorbs atrazine due to less favorable sorption sites of weakly associated alkyl groups on the surface of hydrochar.

Fate of nitrogen content in the hydrochar feedstock is important for plants as well as the environment. However, the availability of N, P, and K was found to decrease sharply during HTC (Zhang et al. 2014; Reza et al. 2013). Employing sulfuric acid ($H_2SO_4$) or potassium hydroxide (KOH) in HTC reduced the P, Ca, Mg, Cl contents, and heavy metal elements (HMEs) in hydrochars (Song et al. 2020). Kruse et al. (2016) reported that the partition of nitrogen in liquid phase and solid phase depended on the biomass and inorganic nitrogen content set free during HTC and precipitated as nitrate or nitrite via the action of available counter ions associated with the hydrochar surface. The high sorption capacity of hydrochars reduced the mineralization of herbicide isoproturon that might reduce the risk of leaching in hydrochar-amended soil (Eibisch et al. 2015b). Recently, Do Santos et al. (2020) reported the availability of humic-like substances from hydrochar that can be used as a new complexing agent to remediate metal-polluted soils.

## Environmental sustainability of hydrochar as soil amendments

Hydrochar is of great interest to the scientific community in using wet biowaste for char production. The availability of raw materials for its production is an issue of high priority for the sustainability of the entire production and application processes. Feedstock can be made available from biodegradable fractions of municipal waste, agro-industrial waste, forest residues, sewage sludge, and animal waste. It is now an imperative to evaluate the environmental sustainability of hydrochar produced from this waste. The life cycle assessment (LCA) approach is required to monitor environmental consequences associated with hydrochar (Berge et al. 2015). LCA is also used to assess the use of hydrochars and their inherent performance (Owsianiak et al. 2017), but currently, there is very little information regarding the LCA of hydrochar as a soil amendment. Recently, Owsianiak et al. (2016) assessed the hydrochars produced from green waste, food waste, organic fractions of municipal solid waste. The authors asserted that HTC is an attractive and promising treatment for biowaste. Doyle et al. (2016) also carried out LCA of hydrochar and developed several impact categories (climate change, ozone depletion, toxicity, land use, eutrophication, water resource depletion, etc.). They concluded that hydrochar as a soil amendment performs better in helping to combat climate change-relevant impact categories. Furthermore, the authors suggested that applying hydrochar reduced the need for irrigation and inorganic fertilizers.

Recently, LCA of HTC from sewage sludge has been reviewed by Meisel et al. (2019) and they explained that the HTC process is acceptable only when a proper HTC optimization process with integrated sewage sludge digestion and recirculation of the HTC process water can be managed efficiently. It is preferred when it also leads to significant reductions in GHG emissions of the HTC concepts. Many environmental aspects of char application in soil for agricultural production have still to be analyzed in more detail, such as the reduction of non-point source pollution of ground and surface waters by fertilizers or other pollutants in agricultural watersheds (Lehmann et al. 2006), effects on N-dynamics in soil or financial benefits associated with char production and application in agricultural practices.

Benavente et al. (2017) compared LCA among HTC, aerobic composting, anaerobic digestion, and incineration. They observed that hydrochar energy recovery results in net environmental benefits. Based on the study by Roy et al. (2020), it was revealed that the life cycle of hydrochars relies on their pathways. The authors noticed that HTC processes are vital to prevent technological and geographic problems in LCA outcomes. Though placing the peat moss on the ground was eco-sustainable, there is no financial benefit and could disrupt the rural economy. Conversely, by using diagnosed peat moss and a combination of peat moss and miscanthus, this would contribute to more activity and to rural development. It would improve rural employment which needs to be seriously incorporated in a future and comprehensive LCA study.

## Conclusions and recommendations

Our knowledge about hydrochar and its potential application as a soil amendment is still very much in its infancy due to currently limited information. From the review, we can conclude that like other carbonaceous materials, hydrochar has encouraging prospects in the context of plant biomass growth and water and nutrient storage capacity. Hydrochar has proved to be effective in retention of toxic substances in the soil due to its complex functional groups although hydrochar itself showed phytotoxicity to plants in some extent. Moreover, hydrochar porosity and C content increase the soil's microbial activity and subsequently elevates its fertility. Hydrochar application with compost may also greatly improve plants' productivity. As a carbon-rich material, hydrochar has been involved in the short-term carbon sequestration process and reduces GHGs. Up to now, marketing and standardized products of hydrochar are still not available, unlike established biochar. Since hydrochar is hydrophobic in nature, there is a possibility of fungal degradation quickly if special care is not taken. There is consequently more scope for systematic research on hydrochar. The following issues need to be addressed in future studies:

- Hydrochars from the blending of two materials by co-HTC process should be checked as soil amendment in lab and field level experiments. The synergistic effects of more than one biomass may reduce toxicity problems that mostly persisted with the hydrochars produced from single materials. Long-term effects of hydrochar application in the fields with varying soil conditions and taking varieties of climate into account should be studied to validate the small-scale lab experiments that have already been done.
- Carbon sequestration potential after hydrochar application, the reduction of greenhouse gas emissions in soil and fate of organic and inorganic compounds should be analyzed more extensively.
- Effect of hydrochar application for stabilization of newly formed islands, salinity reduction, and reclamation of contaminated lands should be studied.

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**Data availability** All data are available.

**Compliance with ethical standards** All sections are relevant to the manuscript.

**Conflict of interest** The authors declare that they have no conflict of interest.

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