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Review

An emerging environmental concern: Biochar-induced dust emissions and their potentially toxic properties

Danielle L. Gelardi, Chongyang Li, Sanjai J. Parikh *

University of California Davis, Land, Air and Water Resources, One Shields Ave., Davis, CA 95616, United States of America

HIGHLIGHTS

- Biochar can increase soil dust emissions or possess elevated levels of pollutants.
- Despite exponential growth of biochar studies, health risks are rarely explored.
- Studies regarding dust, biochar contaminants, and toxicity were reviewed.
- Strategies to minimize harm during production and application were synthesized.

GRAPHICAL ABSTRACT

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ABSTRACT

Amending soils with biochar is increasingly proposed as a solution to many pressing agricultural and environmental challenges. Biochar, created by thermochemical conversion of biomass in an oxygen-limited environment, has several purported benefits, including remediation of contaminated soils, increased crop yields, reduced fertilizer demands, increased plant available water, and mitigation of climate change. Due to these potential benefits, biochar-related research has flourished in the past decade, though there remains a critically understudied area of research regarding biochar's potential impact on human health. Because biochar characteristically has low bulk density and high porosity, the material is susceptible to atmospheric release via natural or mechanical soil disturbance. The specific risks of biochar inhalation have not been elucidated; however, recent publications have demonstrated that biochar can increase soil dust emissions of particles <10 µm (PM_{10}) or possess elevated levels of toxic chemicals. These data should not be interpreted to suggest that all biochars are problematic, but rather to highlight an important and overlooked field of study, and to stress the need to critically assess parameters for biochar production and management strategies that safeguard human health. Here the literature on biochar-related dust emissions and potentially toxic properties (PTPs) is reviewed in order to summarize what is known, highlight areas for future study, and aggregate solutions to minimize potential harm.

Contents

* Corresponding author.
E-mail addresses: dlgelardi@ucdavis.edu (D.L. Gelardi), cyfli@ucdavis.edu (C. Li), sjparikh@ucdavis.edu (S.J. Parikh).

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1. Introduction

The use of biochar, a carbonaceous material created from the thermochemical conversion of biomass in an oxygen-limited environment (International Biochar Initiative (IBI), 2015), as an agricultural soil amendment is an ever-growing topic of interest, eliciting the attention of scientists, policymakers, and growers alike. The number of published biochar studies continues to increase at a near exponential rate, from one publication per annum in the early 2000s, to over 2100 in 2018 (Fig. 1a) (Web of Science). Policymakers have also taken notice, resulting in biochar included as a negative emission technology in the 2018 International Panel on Climate Change (IPCC) Special Report (De Coninck et al., 2018). As scientific and policy interest in biochar grows, so too does the size of the biochar market. Since 2009, over 650 patent applications mentioning "biochar" have been filed with the United States Patent and Trademark Office, over half of which were filed between 2016 and 2018 (Fig. 1b) (US Patent and Trademark Office).

While interest in biochar is evident, many questions remain about the efficacy of biochar use as a soil amendment. Biochar has a number of purported agronomic benefits, including increased water holding capacity (Basso et al., 2013; Novak et al., 2012), increased soil carbon stocks (Atkinson et al., 2010), reduced nutrient leaching (Knowles et al., 2011; Laird et al., 2010; Zhang et al., 2013a), enhanced microbial activity (Kolb et al., 2009), decreased greenhouse gas emissions (Woolf et al., 2014), and the remediation of soil contaminants (Zhang et al., 2013b). Despite the proliferation of biochar studies, research continues to show inconsistent results on the ability of biochar to deliver these benefits, due to differences in biochar feedstock, production methods, soil properties, climate, and cropping systems (Jeffery et al., 2017; Zhang et al., 2016). Meta-analyses and literature reviews have demonstrated that biochar is most likely to deliver agricultural benefits if its production and use is well parameterized for specific outcomes in specific conditions (Jeffery et al., 2017, 2011; Kavitha et al., 2018). This is true not only for agronomic benefits but for climate change mitigation benefits as well. Life cycle assessments (LCAs) have repeatedly shown biochar production and use to reduce current greenhouse gas (GHG) emissions if systems are optimized to minimize biochar transportation, energy inputs, and the use of non-waste biomass products (Dutta and Raghavan, 2014; Gaunt and Lehmann, 2008; Ibarrola et al., 2012; Roberts et al., 2010; Sparrevik et al., 2013). Two of these LCAs also conclude that biochar-related air pollution may contribute to a larger negative effect over its whole life cycle due to potential adverse human health impacts (Ibarrola et al., 2012; Sparrevik et al., 2013). Authors caution that these issues must be addressed before biochar production and use becomes common practice.

While investigation into the agronomic potential of biochar use is well underway, the potential air quality and human health consequences remain critically understudied (Genesio et al., 2016). Biochar is typically characterized by a low bulk density, high surface area, and variable particle size distribution (Downie et al., 2009). While these qualities can provide benefits such as water and nutrient retention, they also render biochar susceptible to its release into the atmosphere as the result of natural or mechanical disturbance. In agricultural settings, this airborne release can occur during biochar application to the soil, or after it has been incorporated as the result of natural wind-driven erosion or through mechanical tillage events. It is well documented that agricultural dust is a major contributor to airborne particulate matter <10 μm in diameter (PM_{10}), particularly in intensively farmed regions (Chow et al., 1992; Madden et al., 2010, 2009). Two recent studies have concluded that soils amended with biochar have the potential to generate significantly more PM_{10} than those without (Li et al., 2018; Ravi et al., 2016).

PM_{10} exposure is a public safety concern as it can bypass the body's particulate interception mechanisms and penetrate deep into the airways. PM_{10} inhalation has been associated with increased chronic respiratory symptoms and the worsening of lung and heart disease (United States Environmental Protection Agency, 2017). Exposure to both the organic and inorganic components from agricultural PM_{10} have been linked with these adverse health effects in farmworkers (Schenker, 2000; Schenker et al. 2009, 2005). While there are chemical, physical,

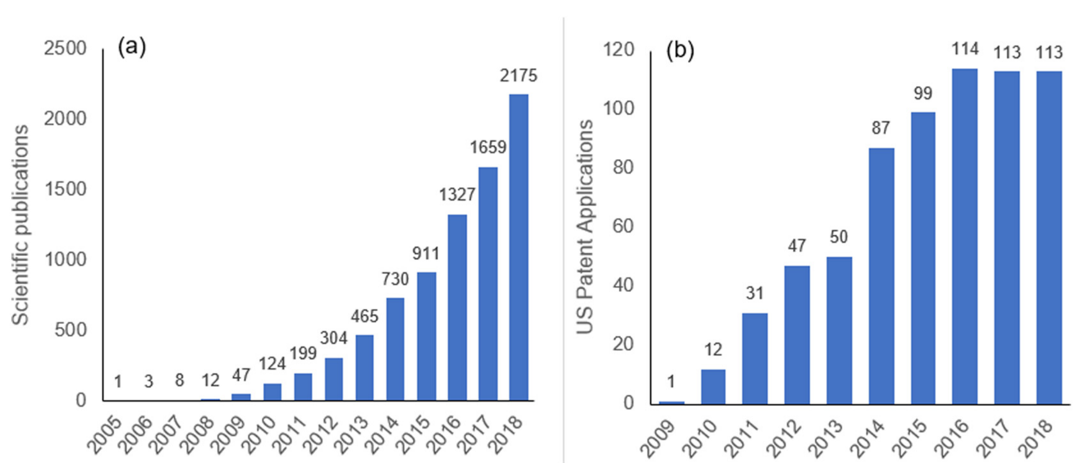

Fig. 1. The increased interest in biochar demonstrated through (a) the number of scientific publications per year with "biochar" listed in available fields and (b) the number of published US patent applications.

and end-use distinctions between biochar and other carbonaceous materials such as coal, there are many chemical and physical similarities (Lehmann and Joseph 2015). These similarities, and what is well known about the linkages between coal inhalation and chronic heart, kidney, and respiratory disease (Castranova and Vallyathan 2000; Graber et al. 2014; Hendryx 2009; Hendryx and Zullig 2009; Santo Tomas 2011), call for further investigation into airborne emissions from biochar-amended soils.

With the growing interest in biochar as a soil amendment comes an imperative to better understand potential consequences for air quality, and how these might affect agricultural workers and neighboring farm communities. While the physical size of biochar-related PM_{10} is itself a serious concern, the organic and inorganic chemical constituents of biochar may also present a human health risk. The primary aim of this review is to highlight the emerging environmental concern of biochar-induced dust emissions by evaluating the limited literature currently available. In addition, solutions to minimize potential harm during biochar production and application are synthesized, and areas for future investigation are suggested.

2. Literature review approach

Web of Science was searched using "biochar AND dust OR toxicity OR health." Studies regarding materials similar to biochar, such as hydrochar, soot, and carbon nanotubes, were excluded, as were studies concerning aquatic environments and waste water treatment systems. There are few studies regarding biochar-induced dust emissions due to the emerging nature of this field, though all available publications concerning this topic were included. Publications regarding biochar polycyclic aromatic hydrocarbons (PAHs), the ability of biochar to bind to soil contaminants, and the ecotoxicological effect of biochar, however, are increasingly available. While authors were careful to include a representative sample of these works, with an emphasis on review papers, recent publications, and studies which investigated multiple biochar production parameters and multiple contaminants, the list of studies included here is not exhaustive. The purpose of this review is not to provide a quantitative assessment, but rather to highlight an emerging environmental concern. As such, a selection of publications was included which contribute to the overall objectives of summarizing the current state of knowledge and highlighting areas for future study.

3. Biochar and dust emissions

In a series of wind tunnel experiments designed to simulate natural erosion processes, Ravi et al. (2016) demonstrated a significant increase in PM_{10} emission in a sand, sandy loam, and silt loam amended with a pine biochar produced by slow pyrolysis at 300 °C, compared to the unamended controls (Ravi et al. 2016). PM_{10} emissions were generally higher in all soils at all biochar application rates at all wind velocities. Authors hypothesize this to be the result of fine biochar particles becoming airborne, and the eventual abrasion of larger biochar particles into those with diameters <10 μm. The latter mechanism is explained through a phenomenon known as saltation bombardment, in which soil particles too large for airborne emission move across the soil surface and erode less stable particles (Fig. 2).This hypothesis suggests that fine biochars, or coarse biochars in sandy soils, may contribute to the highest rates of biochar-induced PM_{10} emissions. This may have far reaching implications for the use of biochar as a soil amendment, as many studies show highest levels of nutrient and water retention in coarse textured soils (Jeffery et al. 2011).

The mechanisms proposed by Ravi et al. (2016) assume the increased PM_{10} to be comprised of biochar itself, though authors do not analyze PM_{10} for its individual soil or biochar constituents. Li et al. (2018) similarly demonstrated an increase in PM_{10} from biochar-amended soils, though the increase was not universal for all biochars tested (Li et al. 2018). In this study, mechanical tillage in a silt loam

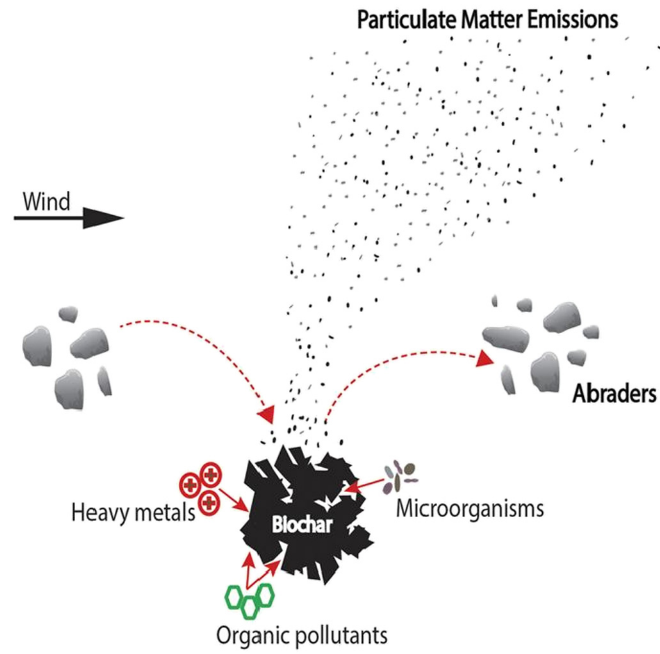

Fig. 2. A conceptual model of particulate matter emissions from biochar-amended soils. Reproduced from Ravi, S., Sharratt, B.S., Li, J., Olshevski, S., Meng, Z., Zhang, J., 2016. Particulate matter emissions from biochar-amended soils as a potential tradeoff to the negative emission potential. Sci. Rep. 6, 1–7. https://doi.org/10.1038/srep35984

and sandy loam was simulated and PM_{10} emissions, as well as the quantity of biochar in the $PM_{10,}$ was measured. In soils amended with a walnut shell biochar produced through gasification at 900 °C (WS900), dust emission increased with increasing biochar amendment rate, and was higher in the silt loam than in the sandy loam. Interestingly, however, concentrations of biochar in the PM_{10} did not increase with increased application of WS900. This indicates that the presence of WS900 induced soil particles themselves to be released into the atmosphere. A chemical analysis of all biochars used in the study showed that WS900 had the highest concentration of K^+ and Na^+, monovalent cations known to have a dispersive effect on soil particles. It is hypothesized that this dispersive effect lead to aggregate instability and colloid mobilization, thus making the amended soil more susceptible to dust emission. This biochar-induced colloid dispersibility is consistent with the findings of other researchers (Kumari et al. 2017).

Together these studies indicate that biochar soil amendments have the potential to increase PM_{10} emissions during natural and mechanical soil disturbance. As previously described, toxicity of PM_{10} is not only attributed to its chemical composition but also its size, and the inhalation of PM_{10} materials is associated with respiratory and heart ailments (United States Environmental Protection Agency 2017). Despite the potential magnitude of this emerging environmental hazard, and the rise in biochar-related publications (Fig. 1), few studies ($n = 5$) have been conducted on biochar-induced dust emissions and the associated risks (Table 1). More research is needed to better understand the mechanisms by which an increase in dust emission occurs, and which combinations of soil and biochar physical and chemical properties are most likely to lead to hazardous outcomes. It is important to highlight that the work of Ravi et al. (2016) and Li et al. (2018) investigates only the short-term residence of biochar in soil, and that both studies were conducted in laboratory settings. Additional research, particularly that conducted at field scale, is required to evaluate how dust emissions may change as biochar forms physio-chemical complexes within the soil. Nevertheless, these studies, as well as those concerning concentrations of PTPs in biochar particulate matter (Table 1), serve as a cautionary note to land managers and policymakers, particularly within intensively farmed regions.

Table 1
Summary of publications regarding biochar-induced dust emissions.

Primary finding	Suggested mechanism	Source
Increase in PM_{10} in biochar-amended soils	PM_{10} comprised of biochar: fine biochar particles become airborne; larger particles are abraded into finer particles	Ravi et al. 2016
Increase in PM_{10} in biochar-amended soils	PM_{10} comprised of soil: elevated levels of monovalent ions from biochar cause dispersal of soil particles	Li et al. 2018
Biochar produced from moist rice husk generated: 1.2–1.6× more PM; 2.1–2.8× more PM-bound PAHs, than biochar from dried rice husk	PM and PAHs generally formed through incomplete combustion of volatiles; incomplete combustion worsened in the presence of moisture	Dunnigan et al. 2018
PAHs in PM 5.4× higher under low (200 mL/min) inert gas flow rate compared to high (800 mL/min)	Longer residence time of volatiles: enhanced secondary reactions to form PAHs; enhanced collisions among PAHs and PM	Ko et al. 2018
<0.75% of biochar PAHs released into simulated lung fluids	PAHs physically entrapped within biochar microporosity, resulting in strong desorption hysteresis	Liu et al. 2019

Abbreviations: $PM_{10,}$ particulate matter <10 μm in diameter; PM, particulate matter; PAHs, polycyclic aromatic hydrocarbons.

4. Biochar as a potential source of toxic compounds

Research has shown that carbon black, a material similar to biochar, exhibits increasing toxicity to the cells of humans and mice with decreasing size (Kong et al. 2013; Sahu et al. 2014). Table 2 provides a selection of studies which also demonstrate cytotoxicity or phytotoxicity as the result of direct contact with biochar, under some or all experimental conditions. As in the carbon black studies, Sigmund et al. (2017b) hypothesize the cytotoxic effect to be the result of the fine particulate nature of biochar. While this suggests that the size of biochar-related PM_{10} is itself a serious threat to human health, the chemical constituents in PM_{10} can offer their own unique hazards.

PAHs, for example, are known to form during the pyrolysis of biomass, with biochar PAH concentration heavily dependent on production methods, feedstock, and temperature (Buss et al. 2016; Hale et al. 2012; Liu et al. 2008). While some biochars contain PAH concentrations well below environmental quality standards (Freddo et al. 2012; Hale et al. 2012; Shackley et al. 2012), others have values well beyond (Hale et al. 2012; Hilber et al. 2012; Keiluweit et al. 2012; Oleszczuk et al. 2013; Schimmelpfennig and Glaser 2012). High PAH concentration in biochars has been linked with mortality of crustaceans (*D. magna*) (Oleszczuk et al. 2013), inhibition of urease enzyme activity (Liu et al. 2018), *Salmonella*/microsomal mutagenicity (Anjum et al. 2014), and inhibition of *V. fischeri* luminescence (Gondek et al. 2017).

Biochars analyzed by Hale et al. (2012) indicate that slow pyrolysis at high temperature (550–900 °C) is likely to minimize PAH content, while those produced through fast pyrolysis and gasification may have the highest levels. This is consistent with the findings of other researchers, who have described a process called pyrosynthesis, in which gaseous hydrocarbon radicals are generated under high temperatures (> 500 °C) via cracking of organic material (Garcia-Perez 2008). These radicals then undergo a series of biomolecular reactions to form polyaromatic rings. High temperatures can also facilitate the fusing of lighter molecular weight PAHs into heavier, more toxic PAHs, which can more easily condense back into the biochar. PAH formation under high temperatures can be minimized through the use of slow pyrolysis, as lighter PAHs have time to volatilize from the system (Ledesma et al. 2002), and by increasing the flow of carrier gases during biochar production (Buss et al. 2016; Ko et al. 2018; Madej et al. 2016). The gasification process, which involves an additional oxidative step, has also been shown to lead to high PAH yields, as oxygen is vital to form certain PAH precursors (Björkman and Strömberg 1997).

Though PAHs can pose a serious threat to human health, a recent study has shown little to no release of PAHs from biochar in simulated lung fluids, indicating that biochar PAHs may not be readily bioavailable through inhalation pathways (Liu et al. 2019). Additionally, the concentration and toxicity of PAHs has been shown to decrease as biochar ages (Oleszczuk 2018; Sigmund et al. 2017a).

Other native toxicants formed during biochar production may include heavy metals, volatile organic compounds (VOCs), dioxins, furans, and PCBs. Heavy metals occur naturally in biomass feedstocks and are concentrated in biochar through the production process (Shackley et al. 2012). As with PAHs, many studies demonstrate biochars to have metal concentrations well below most environmental quality standards (Devi and Saroha 2014; Freddo et al. 2012; Oleszczuk et al. 2013; Shackley et al. 2012). Biochar copper and zinc levels, however, have been observed to have phytotoxic effects in cucumber, cress, and sorghum (Visioli et al. 2016). Similarly, high levels of VOCs have been detected in biochar and observed to cause phytotoxicity in cress (Buss and Mašek 2014). In contrast, observed levels of total dioxins, PCBs and furans in biochar are often very low (up to several pg g^{-1}), with bioavailable fractions below analytical detection limit (Conesa et al. 2009; Hale et al. 2012).

Table 2
Selection of publications on biochar-related toxicological impacts and suggested mechanisms.

Toxicological impact	Suggested mechanism	Source
Phytotoxicity	Exposure to: **1.** PAHs; **2.** Volatile organic compounds; **3.** PAHs and/or HM; **4.** Volatile fatty acids and/or nitrogen-containing organic compounds; **5.** High pH, EC, and/or ammonia gas production; **6.** High pH, EC, and/or HM	**1.** Oleszczuk et al. 2014; **2.** Buss and Mašek 2014; **3.** Li et al. 2015; **4.** Rombolà et al. 2015; **5.** Amaro et al. 2016; **6.** Visioli et al. 2016
Cytotoxicity	Exposure to: **1.** PAHs; **2.** PAHs; **3.** Unknown; **4.** $PM_{2.5}$ bound to cell surface; **5.** Low molecular weight aromatic compounds; **6.** Exposure to compounds in biochar mobile matter	**1.** Oleszczuk et al. 2013; **2.** Gondek et al. 2017; **3.** Mierzwa-Hersztek et al. 2017; **4.** Sigmund et al. 2017b; **5.** Wang et al. 2017; **6.** Yang et al. 2019
Additional adverse effects: **1.** Mutagenesis; **2.** Earthworm avoidance; **3.** Urease inhibition	Exposure to: **1.** PAHs; **2.** High pH, EC, and/or ammonia gas production; **3.** PAHs, HM, and/or oxidative reactions with biochar free radicals	**1.** Anjum et al. 2014; **2.** Amaro et al. 2016; **3.** Liu et al. 2018

Abbreviations: PAHs, polycyclic aromatic hydrocarbons; HM, heavy metals; EC, electrical conductivity; $PM_{2.5,}$ particulate matter <2.5 μm in diameter.

5. Biochar-bound pollutants

A growing number of researchers are examining not only pollutants formed as the result of biochar production, but those bound to biochar as well. Biochar is a sink for a broad range of soil pollutants. Negatively charged sites on biochars can facilitate electrostatic affinity for positively charged heavy metals, for example, making it effective at binding lead, chromium, cadmium, nickel, copper, and zinc in soil (Bair et al. 2016; Beesley and Marmiroli 2011; Cao et al. 2011; Choppala et al. 2012; Fellet et al. 2011; Inyang et al. 2012; Zhang et al., 2013b). The high aromaticity, large surface area, and microporosity of biochar have also been shown to make it an effective agent at immobilizing organic pollutants, including compounds in pesticides (Bair et al. 2016; Cao et al. 2011; Wang et al. 2015) and pharmaceuticals (Bair et al. 2016; Yao et al. 2012), as well as other harmful pollutants such as polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/DFs) (Chai et al. 2012), polychlorinated biphenyls (PCBs) (Denyes et al. 2012; Wang et al. 2013), and PAHs (Chen and Yuan 2011; Khan et al.

2015). A more comprehensive list of studies regarding heavy metal and organic contaminant sorption to biochar prior to 2013 was detailed in a review paper by Zhang et al. (2013b).

While the immobilization of pollutants may reduce their bioavailability, leaching, and volatilization from the soil (Zhang et al., 2013b), it is troubling from the perspective of dust emissions, as biochar-bound pollutants may also be released into the atmosphere and made available for human inhalation. Together, these pollutants represent neurotoxins, carcinogens, mutagens, and reproductive toxins, many of which become acutely hazardous through inhalation. At present, there is a dearth of research examining the potential for biochar-bound substances to become airborne. There is an urgent need for investigation into this topic, particularly in locations where biochar is used expressly for soil remediation purposes.

6. Proposed regulations

The United States has not yet adopted regulatory standards for biochar contaminant levels, though maximum threshold values for a limited number of toxicants have been established in frameworks proposed by the European Biochar Certificate (European Biochar Foundation (EBC) 2016) and the International Biochar Initiative Guidelines (International Biochar Initiative (IBI) 2015) (Table 3). Differences in these standards have led to inconsistencies in both scientific and legislative literature. There is a pressing need for a unified regulatory framework, which would facilitate communication in academic fields and in the emerging biochar market.

An additional challenge presented by EBC and IBI criteria is that threshold values represent 'total' concentrations, measured through robust acid digestion for heavy metals, or by exhaustive solvent extraction for organics. These methods tend to overestimate the fraction of 'bioavailable' toxicants and therefore the ecotoxicological effects. More research is needed on how toxicants may be released from biochar over time and made available to the human respiratory system. This field of study would assist in refining the conceptual definition of the 'bioavailable' toxicants in biochar and contribute to safer, more consistent regulatory standards. Finally, attempts should be made to investigate additional unknown, but potentially hazardous toxicants, carcinogens, or endocrine-disruptors in the biochar matrix using non-target analysis techniques, in order to expand regulations to include additional biochar-related risks.

Table 3
Maximum threshold values of heavy metals/metalloids and organic compounds for biochars.

Elements or compounds	European Biochar Certificate		International Biochar Initiatve
	Basic grade	Premium grade	
As (mg kg^{-1})	n.a.	n.a.	13–100[a]
Cd (mg kg^{-1})	1.5	1	1.4–39[a]
Cr (mg kg^{-1})	90	80	93–1200[a]
Co (mg kg^{-1})	n.a.	n.a.	34–100[a]
Cu (mg kg^{-1})	100	100	143–1500[a]
Hg (mg kg^{-1})	1	1	0.8–17[a]
Mo (mg kg^{-1})	n.a.	n.a.	5–75[a]
Ni (mg kg^{-1})	50	30	47–600[a]
Pb (mg kg^{-1})	150	120	121–300[a]
Se (mg kg^{-1})	n.a.	n.a.	2–36[a]
Zn (mg kg^{-1})	400	400	416–2800[a]
PAHs (mg kg^{-1})	12	4	6–20[a]
PCBs (mg kg^{-1})	0.2 (I-TEQ)	n.a.	0.2–0.5[a]
Dioxins (ng kg^{-1})	20 (I-TEQ)	n.a.	9
Furans (ng kg^{-1})	20 (I-TEQ)	n.a.	9

Abbreviations: PAHs, polycyclic aromatic hydrocarbons; PCBs, polychlorinated biphenyls; n.a., not available.

[a] The maximum allowed threshold values have a range because they are from a number of jurisdictions including EU, Australia, Canada, USA and Quebec.

7. Strategies to mitigate potential harm

To our knowledge, no research has been conducted to compare strategies to minimize biochar-induced dust emissions and the associated risks, though common-sense suggestions and best practices can be found throughout biochar literature. Major (2010) summarizes various biochar application methods and recommends combining biochar amendment with other on-farm processes to reduce costs and to minimize the potential for dust emissions (Major 2010). Suggestions include adding biochar to compost, liquid fertilizer, or lime. To reduce dust emissions, recommendations for applying biochar with high moisture content or in liquid slurries are common, as are warnings to avoid application on windy days (European Biochar Foundation (EBC) 2016; Sigmund et al. 2017b; Silva et al. 2015). While most biochar field trials utilize a broadcasting application technique (Fig. 3a), Major (2010) suggests that subsurface banding (Fig. 3b) may have the greatest potential to reduce wind and rain-driven biochar losses. To date, very few studies have utilized this technique (Blackwell et al. 2010). Regardless of application method, the use of appropriate respirators, eye protection, gloves, long sleeves and pants is recommended for farm operators and workers while handling biochar (Schwab and Hanna 2012).

The above strategies address the one-time health hazard presented by the application of biochar, but do not address the risk of continued dust emission after biochar has been incorporated. The work of Ravi et al. (2016) and Li et al. (2018) demonstrate this to be a potentially serious concern, though it is unclear if increased residence time of biochar in soil would increase or decrease health risks. While biochar may become unavailable for airborne emission through mineral and organic complexation and aggregation, it may also have increased time to form complexes with soil pollutants, rendering toxicants susceptible to atmospheric emission as well. Subsurface banding may have a role in reducing biochar-induced PM_{10} emissions, as it buries biochar deep below the soil surface and places it at the rooting zone of the plant rather than throughout the bulk soil. Additionally, research indicates that increasing soil water content can exponentially reduce dust emissions (Li et al. 2018; Madden et al. 2009). Therefore, it can be concluded that mechanical tillage activities should not be undertaken when biochar-amended soil is dry. Tilling wet soil can lead to compaction and clodding, however, and so special attention should be paid to regionally-specific ideal moisture conditions.

Li et al. (2018) demonstrate that a high concentration of monovalent ions has the potential to disperse soil particles and increase dust emissions, while the findings of Ravi et al. (2016) indicate that particle size distribution combined with soil texture are determining factors for dust emissions. These properties should be considered before choosing a biochar and incorporating it into the soil, as should the levels of potentially toxic elements.

During the biochar production process, steps can be taken to create a safer, more effective soil amendment. As heavy metals and metalloids are concentrated in biochar through pyrolysis (Shackley et al. 2012), the use of treated feedstocks such as Chromated Copper Arsenate (CCA)-pressure treated wood should be avoided, along with materials from construction and demolition, and feedstocks of unknown origin. Research suggests that slow pyrolysis may minimize biochar PAH content compared to gasification, and that increased residence time (Hale et al. 2012) and carrier gas flow (Buss et al. 2016; Ko et al. 2018; Madej et al. 2016) can offset PAH formation under high temperatures. There may also exist simple pre- and post- production modifications that reduce levels of PTPs. Studies indicate that drying feedstock biomass prior to pyrolysis may reduce production-related PM_{10} emissions, as well PM-bound PAHs, as the presence of moisture encourages the incomplete combustion of volatile compounds formed during pyrolysis (Dunnigan et al. 2018). Research has also demonstrated that biochars

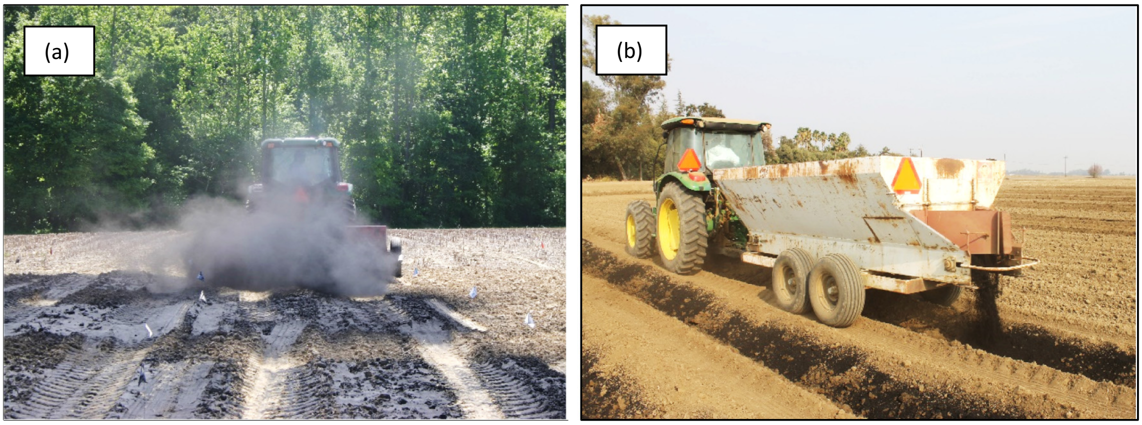

Fig. 3. Biochar applied to a field using (a) a broadcasting technique of a dry biochar and (b) subsurface banding of a biochar at 40% moisture content. Photo credit for 2a to Brian Kozlowski at the University of Tennessee.

can be dried at temperatures between 100 and 300 °C, effectively removing PAHs through thermal desorption within 24 h (Kołtowski and Oleszczuk 2015). Efforts have also been made to improve the physical properties of biochar during its production. An increasingly popular technique is to pelletize biochars to increase resistance to abrasion (Reza et al. 2012). Addition of binders during pelletization, such as lignin and $Ca(OH)_2$, can further enhance the mechanical strength of biochars (Hu et al. 2015). With increased mechanical strength and abrasion resistance, biochar may emit less dust compared to those that have not been compressed.

8. Concluding remarks

Perhaps the most salient conclusion that can be drawn from the limited literature on biochar-induced dust emissions and their PTPs is the importance of knowing the physical and chemical properties of biochar prior to amendment in the soil. Regulators and biochar producers have a great responsibility to work with land managers and growers to ensure the safe and effective use of this increasingly popular soil amendment. Despite the proliferation of biochar studies, a disproportionately small fraction investigate biochar-induced dust emissions, PTPs, and ecotoxicity. As interest in biochar use rapidly grows, it is imperative to address the gaps in knowledge concerning the potential impact on human health. Areas for future investigation include the mechanisms by which biochar may increase PM_{10} emissions, and the soil and biochar properties most likely to lead to hazardous outcomes. Future research is also required on the chemical composition of biochar-induced PM_{10}, in order to determine the concentrations of biochar and biochar-bound pollutants potentially available for human inhalation. As research into these areas expands, it is also necessary to investigate strategies to reduce potential harm during biochar production and incorporation of biochar into the soil, and to create clear, unified environmental quality standards across regions and disciplines.

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