



Review article

Effect of production conditions on self-heating propensity of torrefied sawmill residues



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HIGHLIGHTS

- Self-heating screening of bio-chars torrefied under different conditions.
- Bio-char properties affecting self-heating propensity based on a coal self-heating review.
- Higher self-heating propensity on bio-chars compared to un-treated materials.

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ABSTRACT

In this work, a screening of the self-heating propensity of bio-char produced from softwood bark and sawdust under different torrefaction conditions was performed. As there is an abundance of information regarding coal self-heating behavior, the bio-char evaluation was based on a review of coal self-heating and the tests used to evaluate the behavior. Bio-char physical and chemical properties, such as; proximate analysis, heating value, porosity, ash composition, and mineral composition, were determined and analyzed for impact on self-heating. Bio-char had a higher susceptibility for self-heating when compared to the feedstock as torrefaction increases carbon content and depletes volatile compounds resulting in an increase in available oxidation sites. The bio-char self-heating propensity increased with torrefaction temperatures under the range studied. This increase is likely not due to an increase in porosity as there is little difference in the porosity between chars studied from different feedstocks or temperatures and residence times. The self-heating propensity increases with fixed carbon content.

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Contents

1. Introduction	227
2. Coal self-heating	228
3. Torrefaction experiments	230
4. Torrefaction self-heating analysis	231
5. Conclusions	235
Acknowledgments	235
References	235

1. Introduction

Bio-char is the product of torrefaction (slow pyrolysis at mild temperatures), and by-product of the pyrolysis or gasification of biomass and has a number of possible applications from solid fuel to adsorbents [1,2]. Torrefied fuels feedstocks studied include

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agricultural crops/residues [3], forestry residues [4], municipal wastes [5], etc. Bio-char can also be generated in smaller quantities as a by-product of high temperature pyrolysis [6] and gasification [7]. Regulations on emissions from coal power plants are becoming more restrictive, as such torrefied biomass (bio-char) can offer a cleaner alternative to coal [8–10]. High torrefaction temperature bio-chars have an energy content comparable to low rank coals [3] and better energy density compared to biomass, less toxicity associated with emissions from combustion, homogeneous combustion behavior, high grindability and low hygroscopy [11]. These properties make bio-chars an ideal alternative to coal and other solid fuels. To safely use it as a fuel we must establish safe handling and transport procedures. Some bio-chars can undergo self-heating, depending on the parent biomass and pyrolysis conditions. As such, the degree and prediction of when and why self-heating occurs is critical.

Self-heating is the spontaneous combustion of a material undergoing slow oxidation [12]. Material self-heating can be a consequence of reactions by decomposition, contamination and autocatalysis but in most cases is due to a slow oxidation by air exposure [13]. A material can develop self-heating during processing, storage and transport [12]. Other materials reported to develop self-heating are: coal [14], petroleum coke, discarded piles of railway tie dust, and asphalt particles [15], biomass piles for fuel application [16] such as wood pellets [15] and miscanthus chips [17], seasonal storage of refuse derived fuel [18], municipal solid waste [19], compost, landfills [20], sulfide minerals [21,22] and various agricultural products [23]; e.g. hay [24,25], wheat, barley, soybeans, flour [26], wool [27], etc.

The self-heating process initiates at a low temperature and increases with the reaction heat release. At higher temperatures, self-heating is limited by oxygen diffusion which reduces the increase in heat released as function of temperature. The temperature at which material is stored and loaded into a vessel, pile, or reactor determines self-heating behavior and risk of run-away reactions. The size of piled material also influences self-heating, while small piles could be safely stored, larger piles of the same material could exhibit self-heating behavior due to lower capacity of heat removal through pile boundaries. Water content and humidity in the environment have a more complex effect. Water can accelerate self-heating as it catalyzes self-heating reactions and the adsorption of water increases heat generated. Water vaporization withdraws heat and delays self-heating but the vaporization–condensation also increases material conductivity. The overall water effect is to increase the onset self-heating temperature [12].

Self-heating is a well recognized issue in the coal industry [14] and substitution with bio-chars or biomass where the quantity of material is very large can encounter similar issues [16,28]. Self-heating behavior of bio-chars has been reported as smoldering/fire incidents in storage, right after production [28–30]. Bio-char self-heating has been studied for specific feedstocks and processes; a review on these studies up to 2003 is found in Antal and Grønli [31]. Bio-char self-heating studies include: bio-chars derived by fast pyrolysis [32], slow pyrolysis [33] including torrefaction [30,34]. Bio-char self-heating has been reported on various scales from laboratory [30,32] to pilot plants [28].

General safety precautions commonly used to mitigate self-heating include; (1) material cooling, (2) periodic material mixing, (3) oxygen reduction, or use of inert gases, (4) addition of materials which inhibit oxidation, (5) weathering hygroscopic material to avoid adsorption heat release before compaction and storage [12].

The bulk studies on bio-char produced by torrefaction focus on: bio-char fuel product quality [35–40], bio-char pelletization [1,36,41,42] bio-char processes [1,43] and, co-firing of bio-char

with coal [9,44]. There are few studies focused on the safety aspect related to self-heating which should develop along with bio-char technology [28]. Some torrefaction studies point out a benefit of processing within certain conditions (temperature, time) for fuel [36,38] or others applications [45], but typically do not address highly torrefied biomass. There is also a gap relating torrefaction process conditions with self-heating propensity.

This work presents a screening analysis of the self-heating propensity of bio-chars from two forestry residues (softwood sawdust and bark) under different torrefaction conditions. The bio-char's physical and chemical properties are characterized to determine impact on self-heating behavior. Self-heating is assessed based on a review of coal self-heating assessment methods. This work first summarizes important coal properties affecting self-heating, and a review of analytical methods used in self-heating evaluation of coals. The review is used to assess self-heating of torrefied bio-char derived from softwood sawmill waste.

2. Coal self-heating

Coal self-heating is a major safety and production problem at active mines [46,47], and preparation and processing plants [48]. Coal stock piles, silos, mills and transportation vessels can develop self-heating creating hazards such as fires, harmful gas emissions, and explosions [49]. Abandoned mines, and banks of waste rejects are also prone to self-heat [50,51]. Fig. 1 outlines the complexity of the coal self-heating process [14,52,53]. Coal characteristics impacting self-heating include but are not limited to: elemental composition, moisture content, fix and volatile carbon, ash matter, sulfur content, surface area, porosity distribution, energy content, heat capacity and particle size. Surroundings also impact self-heating such as; humidity, ambient temperature and oxygen concentration [54,55].

Efforts have been made to determine the relationship between coal composition and self-heating by studying representative samples of different coal ranks but conclusions vary widely. Low rank coals (lignite, subbituminous) have been associated with increased self-heating propensity compared to high rank coals (bituminous and anthracites) [48,49,56–58]. However, other studies conclude that rank cannot give a direct indication of self-heating [47]. Rank characterization is done by fixed carbon and calorific value [59] and by volatile content or by oxygen:carbon and hydrogen:carbon ratios (on a dry and mineral free basis) [60]. Coals of the same rank can also differ in moisture, mineral matter [56], porosity and oxidation history [14]. The differences in bio-char composition and structure as a function feedstock and pyrolysis conditions are analogous to the problems associated with simple correlation of rank of coal with self-heating.

In the bulk of studies on coal mineral content and self-heating, pyrite is typically the mineral of study (FeS_2) [21,22,61,62]. Pyrite concentration as low as 2 wt% can pose an acceleration effect on coal self-heating [22]. Other Inorganic additives mixed with coal in 5–15 wt% quantities have been found to accelerate or inhibit self-heating [61,63]. Bio-char ash content derived from agricultural residues is low compared to most coals, and sulfur is not typically present. However, given the impact of ash and mineral content on self-heating on coal the area will be reviewed.

The overall surface area due to pores in coal is much larger than the external coal surface area, and therefore oxidation is mainly a pore phenomenon [54,57]. Pore distribution is also important for accessibility and diffusion of oxygen through the particle, the same concept applies to a pile of coal which determines the capacity for oxygen diffusion and oxidation on a coal pile [64]. This will also apply to bio-chars. Coal moisture content can delay self-heating

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