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An Overview of Microwave Assisted Pyrolysis for Waste Management, with Some Thoughts about Processing Industrial Hemp and Other Woody Wastes

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Abstract

The generation of waste is significantly influenced by the increase in population and industrialization, thereby compelling the increased demand for waste management and resource recovery. This paper investigates the potential opportunities presented by the utilization of microwave-assisted pyrolysis for processing plastic and organic waste materials, with a particular focus on industrial hemp leaves, hurds, and root materials, and other feedstocks. Drawing from a range of published studies, it is suggested that microwave-assisted pyrolysis has the potential to achieve energy neutrality or even energy generation, if all byproducts are used. Depending on factors such as recoverable volumes and the associated recovery costs of commercially significant chemicals like vinegars and bio-oils, the microwave-assisted pyrolysis of industrial hemp leaves, hurds, and root materials may prove to provide high return of the yield and profits. Additionally, this paper explores the production of other valuable byproducts such as syngas and biochar from alternative feedstocks, particularly when data related to hemp processing is not readily available.

Keywords

Waste Management, Microwave Assisted Pyrolysis, Organic waste, Biochar, Bio-oil, Syngas

1. Introduction

1.1 Difficult Waste Streams

Plastic waste streams are difficult to manage. Plastics from land fill do not break down in the environment, but become microplastics, which can contaminate the environment and the food chain (Shirvanimoghaddam, Czech, Yadav, et al., 2022) and incineration ultimately results in air pollution and contributes CO₂ to the atmosphere. Plastic waste is generated by many industries, including agriculture, horticulture, and medical facilities. One of the challenges of agricultural and horticultural plastic waste is contamination from agricultural chemicals, which limits recycling options (Briassoulis et al., 2013). Since December 2019, the recent novel coronavirus (SARS-CoV-2), or COVID-19, pandemic has dramatically increased medical waste production by healthcare facilities (Patrício Silva et al., 2021). As an example, King Abdullah University Hospital, in Jordan, generated approximately 650 kg per day of additional medical waste from 95 COVID-19 patients (Patrício Silva et al., 2021). Most medical waste consists of single use, plastic items, which are disposed of by incineration or contribute to land fill. Both the disposal methods contribute to environmental degradation.

Bio-waste streams, such as biosolids (stabilised sewerage and animal production waste sludge) and waste from food and fibre processing, can also be regarded as either problematic or recalcitrant materials. For example, between 2008 and 2013 Australian biosolids production, derived from sewage sludge, increased from approximately 300,000 dry tonnes (LeBlanc et al., 2008) to 360,000 dry tonnes (Pritchard et al., 2010) annually. While some end uses can be found for these waste materials through processes such as composting (Neeson, 2008) or repurposing, the presence of bio-available heavy metals in many of these wastes preclude their immediate use (Akter et al., 2023; Kabir et al., 2021).

1.2 Waste from Hemp Fibre Industry

Hemp (*Cannabis sativa*) is usually cultivated for its fibre and edible seeds. It can also produce some medicinal products. Hemp fibre production represents a low ecological footprint with 1.46 to 2.01 global hectares (gha). The ecological footprint is the amount of bio-productive area (land and sea area), measured in global hectares, needed for production, and to absorb waste and emission (Duque Schumacher et al., 2020). In comparison with the ecological footprint of cotton fibre ranges from 2.17 to 3.57 gha (Duque Schumacher et al., 2020), hemp offers a substantial advantage.

When fibres are separated from the hemp stem, hemp hurds, which are the woody inner core of the stem, remain. These woody hurds are the least valuable part of the hemp stem and are often treated as a by-product of fibre production, even though they represent the largest fraction of the hemp plant. Although hemp hurds can be used in a range of applications such as animal bedding, construction materials, and garden mulch (Carus & Sarmiento, 2016), in many places they are still generally considered as waste.

Several studies have explored the use of slow pyrolysis to convert hemp hurds into more valuable products (Salami et al., 2021), including biochar, bio-oils, and syngas.

1.3 Pyrolysis

Pyrolysis is the thermal breakdown of various types of carbon-based materials, which can include biowaste, plastics and hemp hurds, in an inert environment at temperatures ranging from 350 to 1,000 °C (Schmidt et al., 2019). This process breaks down carbon molecules, resulting in condensable vinegars, oils (bio-oil), non-condensable gases (syngas) and a residue solid material (biochar) (Schmidt et al., 2019). Thermal processing also captures and retains heavy metals in the biochar, facilitating its potential use in agriculture.

Biochar has been gaining more attention because it also immobilises soil organic and inorganic pollutants and heavy metals, due to its high carbon content, micropores, and large surface area (Kabir et al., 2021). It is porous and rich in stable and resistant carbon, with different surface functional groups (Ahmad et al., 2014). These unique properties of biochar make it an effective sorbent, which can immobilize heavy metals including Cr, Co, Ni, Cd, Zn, Cu, and Pb (Antunes, Jacob, et al., 2017; Antunes, Schumann, et al., 2017; Mohan et al., 2014; Zhu et al., 2016).

To obtain a high yield of the bio-oil component in a conventionally heated pyrolysis process, the feed stock must be rapidly heated and the residence of the volatile component in the hot environment of the pyrolysis chamber must be as short as possible (Yanik et al., 2013). While the feed stock itself will influence the fractionation into the four main products (char, oil, vinegars, or gas), the heating method will potentially favour one or the other of oil or gas production. The resulting char fraction will be inversely proportional to the combined yield of vinegar, oil and gas.

Conventional heating is achieved by placing the processed material into a hot environment, such as a furnace or oven, so that heat is transferred from the environment to the material by convection and then through the material by internal thermal conduction. Electromagnetic heating is achieved by the direct absorption of electromagnetic energy by a material, so the heating occurs volumetrically in the target material and

is then transferred internally from the hot spots in the material to the cooler places by internal conduction. These heating mechanisms are worth exploring in more detail.

2. Heating Methods

2.1 Conventional Heating

Pyrolysis is commonly performed in a batch furnace, auger fed reaction chamber (Nikitina et al., 2018), or fluidised bed system (Yanik et al., 2013). Conventional heating sources include the combustion of external fuels, recycled biogas from the pyrolysis process itself, or by using electricity. In all conventional heating cases, the feedstock material is heated by a combination of radiative absorption and convective heat transfer onto the surface of the material and then heat is transferred from the surface to the core of the material by thermal diffusion through the material (Holman, 1997).

It has been shown that the heating profile in a convective furnace is described by (Shirvanimoghaddam, Czech, Abdikhebari, et al., 2022):

$$T = (T_{\infty} - T_i) \cdot \operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right) + \left[\frac{\varepsilon\sigma(T_{\infty}^4 - T_{ss}^4)}{k}\right] \times \sqrt{\frac{\alpha}{\pi t}} \cdot e^{-\frac{x^2}{4\alpha t}} - \left\{T_{\infty} - T_i + \left[\frac{\varepsilon\sigma(T_{\infty}^4 - T_{ss}^4)}{k}\right] h\alpha\right\} \times \operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha t}} + h\sqrt{\alpha t}\right) \cdot e^{\frac{h}{k^2} \frac{\alpha t h^2}{k^2}} + T_i \quad (1)$$

where $\operatorname{erfc}(z)$ is the complementary error function of parameter z , x is the distance from the surface into the core of the material (m), T_i is the initial temperature of the material (K), α is the thermal diffusivity of the heated material ($\text{m}^2 \text{s}^{-1}$), ε is the surface emissivity of the radiator material, h is the convective heat flow coefficient ($\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$) of the material's surface (Holman, 1997), σ is the Stefan-Boltzmann constant ($5.6704 \times 10^{-8} \text{ J s}^{-1} \text{ m}^{-2} \text{ K}^{-4}$), T_{∞} is the temperature of the surrounding furnace (K), and T_{ss} is the surface temperature of the material being treated (K), k is the thermal conductivity of the heated material ($\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$), and t is time (s).

Using the material parameters woody materials, outlined in Table 1, heating a sample of dry woody material, like hemp hurds, in a convective furnace, which has been pre-heated to $500 \text{ } ^\circ\text{C}$, can require more than 3 hours for the temperature at 2 cm depth to reach $400 \text{ } ^\circ\text{C}$ (Shirvanimoghaddam, Czech, Abdikhebari, et al., 2022).

Table 1: Material parameters used in mathematical models (Holman, 1997):

| Material | Density | Thermal Conductivity | Thermal Capacity |
|----------|--------------------|----------------------------------|-----------------------------------|
| | kg m^{-3} | $\text{W m}^{-1} \text{ K}^{-1}$ | $\text{J kg}^{-1} \text{ K}^{-1}$ |
| Air | 1.2 | 0.026 | 700 |
| Wood | 800 | 0.22 | 2,300 |

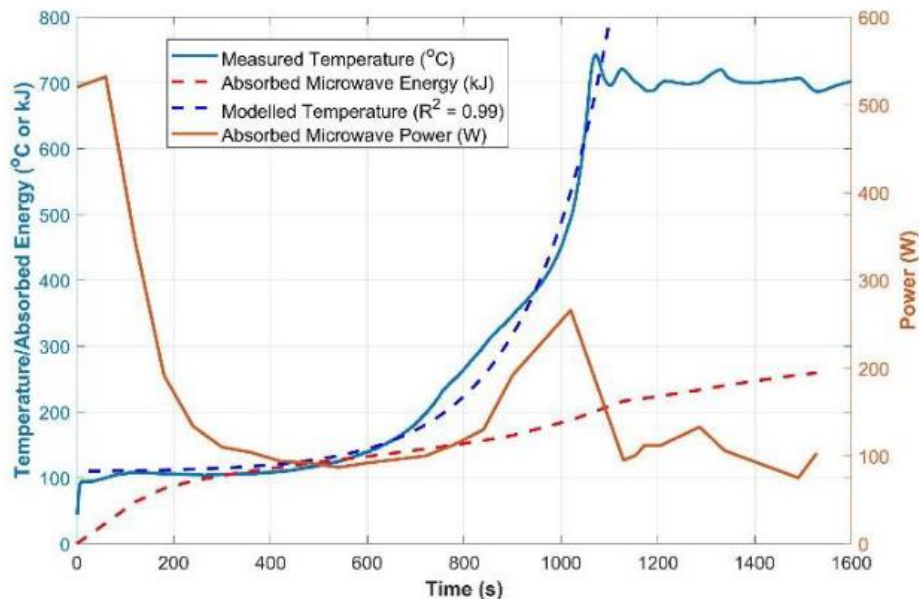


Figure 1: Measured temperature, a temperature model based on equation (2), absorbed microwave power, and absorbed microwave energy analysis of experimental biosolids pyrolysis conducted in a single-mode microwave chamber.

2.2 Electromagnetic Heating

Unlike conventional heating, electromagnetic heating is due to a volumetric absorption of electromagnetic energy in the heated material.

The temperature in a microwave heated material is described by (Brodie, 2008):

$$T = \frac{\omega \varepsilon_0 \kappa'' \tau^2 E_0^2}{8k_s \beta^2} (e^{4\alpha_s \beta^2 t} - 1) \times \left[e^{-2\beta x} + \left(\frac{h}{k_s} + 2\beta\right) \cdot x \cdot e^{-\frac{x^2}{4\alpha_s t}} \right] + T_i \quad (2)$$

where ω is the angular frequency of the microwave field (rad s^{-1}), ε_0 is the permittivity of free space (Farad m^{-1}), κ'' is the dielectric loss factor of the material, β is the surface reflection coefficient of the material, E_0 is the strength of the electromagnetic field at the surface of the material (V m^{-1}), α_s is the thermal diffusivity of the heated material ($\text{m}^2 \text{ s}^{-1}$), and β is the field attenuation factor.

Unlike convective heating, the theoretical temperature in a microwave heated material is unbounded and exponentially growing (i.e., it will keep increasing provided the microwave power is continually applied). It is also apparent that the maximum temperatures are below the surface in microwave heating while they are at the surface in convective heating. Finally, microwave heating is usually much faster than convective heating because the manifestation of heat in the material is not entirely reliant on the thermal diffusivity of the material, as it is in convective heating. For example, using the same material properties listed in Table 1 and dielectric properties for wood as provided by (Torgovnikov, 1993), dry woody material requires about 24 minutes of heating for the temperature at 2 cm depth to reach $400 \text{ } ^\circ\text{C}$ in a 750 W microwave oven, operating at 2.45 GHz (Shirvanimoghaddam, Czech, Abdikhebari, et al., 2022).

The penetration depth of the electromagnetic field is defined as the distance at which the electromagnetic power drops to e^{-1} , where e is the logarithmic base for natural logarithms. The penetration depth is defined by:

$$d = \frac{1}{2 \frac{\omega}{c} \sqrt{\frac{\kappa'}{2} \left[\sqrt{1 + \left(\frac{\kappa''}{\kappa'}\right)^2} - 1 \right]}} \quad (3)$$

where κ' is the dielectric constant of the material and c is the speed of light (m s^{-1}).

This penetration depth of microwaves is a key parameter in evaluating microwave heating (Peng et al., 2010) and for more uniform electromagnetic heating, it is good practice for the material thickness to be comparable to the electromagnetic penetration depth.

The temperature model, presented in equation 2, is consistent with the temperature rise observed in real samples of biosolids (Antunes, Schumann, et al., 2017), as shown in Figure 1. Once the set point was achieved, the applied microwave energy was adjusted to maintain a relatively constant temperature in the sample for a further 10 minutes.

The main advantage of microwave assisted pyrolysis include its flexibility in terms of the wide range of feedstocks that it can process, from biomass and organic residues to plastics, tires and other unconventional materials, including mixed feedstocks such as municipal solid waste (Luque et al., 2012).

Microwave heating also offers significantly better process control compared with conventional heating, which leads to rapid and convenient start-up and shutdown, better process and parameter control (time, temperature, power), and versatility for biomass processing, which generally leads to high quality biochar, oil or gas, with less dependence on the feedstock used (Luque et al., 2012). Heating stops when the electromagnetic source is turned off.

3. Process Control

3.1 Product Yields from Different Processing Conditions

The operating conditions of the microwave system have a crucial effect on the biochar, bio-oil, vinegar, and biogas yield. Some influencing factors are input power, microwave susceptor type and concentration, vacuum pressure in the system, heating rates, nitrogen flow, and geometry of the processing chamber (Allende et al., 2023). For instance, high reaction temperatures and pyrolysis power produce low biochar yield but high biogas yield. A higher heating rate promotes the rapid formation of volatiles, and high chamber temperatures cause secondary reactions in the chamber atmosphere, converting condensable vapours (what would normally become oils and vinegars) into syngas.

A longer reaction time is beneficial for biochar and bio-oil yield. A prolonged thermochemical conversion and low power produces a high enough temperature to complete the pyrolysis process but reduces the secondary breakdown of organic vapours and increases the release of volatiles for the formation of bio-oils (Allende et al., 2023).

Under microwave assisted pyrolysis, bio-oil, vinegar, and syngas production are almost synchronized, which is a unique advantage of these systems, compared with conventional pyrolysis (Luque et al., 2012). The reason for this is mostly related to the simultaneous heat and mass transfer characteristics of microwave heating (Brodie, 2007), which is associated with the volumetric and instantaneous heating of the feedstock (Luque et al., 2012).

3.2 The Role of Electromagnetic Absorbers in Microwave Assisted Pyrolysis

For microwave-assisted pyrolysis to be effective, the treated waste/biomass should possess dielectric properties which readily absorb the electromagnetic radiation and convert it to thermal energy. Most dry biological and plastic waste materials have very low dielectric properties (Antunes et al., 2018), implying that the material is more transparent to electromagnetic energy and hardly any energy is absorbed and converted to heat; therefore, a microwave adsorber/susceptor material must be dispersed homogeneously throughout the waste material to absorb the electromagnetic energy and then transfer the heat to the dry waste via thermal conduction (Antunes et al., 2018). The choice of susceptor is an important factor to consider when designing a microwave-assisted pyrolysis process. The microwave susceptor material should not contaminate the final pyrolysis by products and not significantly increase the overall costs (Antunes et al., 2018). The microwave susceptor affects the yields of bio-oil/syngas/biochar and controls their physicochemical characteristics (Shirvanimoghaddam, Czech, Abdikheibari, et al., 2022). Several susceptor materials have been trialled in various experiments; however, Carbon-based materials, such as activated carbon or biochar, have proven to be good susceptors. In experiments conducted by Antunes et al. (2018), the inclusion of a Carbon-based microwave susceptor reduced the microwave heating time for their samples from over 1000 seconds (Figure 1) to approximately 250 seconds.

The inclusion of either charcoal or activated carbon resulted in highly stable biochars with excellent surface area. Additionally, from an economical viewpoint, activated carbon susceptor required the lowest microwave power and yielded the highest energy value in the resulting syngas, bio-oil, and biochar products (Shirvanimoghaddam, Czech, Abdikheibari, et al., 2022).

3.3 Feedstock

In addition to the processing conditions, all products of pyrolysis are affected by the feedstock material used in the pyrolysis system. In conventional pyrolysis systems, biochar properties are affected by feedstock. For example, biochars produced from animal litter and solid waste feedstocks exhibit lower surface areas, carbon content, volatile

matter and high cation exchange capacity compared with biochars produced from crop residue and woody biomass, even at higher pyrolysis temperatures (Tomczyk et al., 2020). This may be due to the considerable variation in lignin and cellulose content within the different feedstocks as well as in moisture content of biomass.

In the study by Salami et al. (2021) liquids were recovered from the slow pyrolysis of industrial hemp leaves, hurds, and roots at a pyrolysis temperature of 275–350 °C, and at two condensation temperatures 130 °C and 70 °C. Their study was conducted using a conventional pyrolysis system, heated using an electrical element. Both aqueous vinegars and bio-oil pyrolysis liquids were produced during the pyrolysis process.

4. Products

4.1 Aqueous Vinegars

The products of pyrolysis are biochar, bio-oil, aqueous vinegars, and syngas. The aqueous vinegars, which are generally acidic, are associated with both free and bound water in the feedstock materials. For example, in the aqueous fractions derived from Salami et al. (2021) pyrolysis of hemp leaves, hurds, and roots the concentration range of acetic acid was 50–241 g L⁻¹, methanol 2–30 g L⁻¹, propanoic acid 5–20 g L⁻¹, and 1-hydroxybutan-2-one 2 g L⁻¹. Acetic acid was one of the main compounds from the aqueous fraction and its yield would be about 40 kg ton⁻¹ of feedstock with a value less than AU\$ 170 as a bulk product with low purity (Salami et al., 2021).

According to Salami et al. (2021) the remarkable difference between hemp leaves, hurds, and roots is the presence of 1-hydroxybutan-2-one, which can only be extracted from the hemp hurds. It is the most expensive compound found in their study, with a value of AU\$ 33.63 – 168.15 g⁻¹ (Salami et al., 2021), and the total amount in the distillates is roughly 1.3 kg ton⁻¹. In general, this could be purified to higher than 95% purity.

4.2 Bio-oil and Syngas

Direct experimental data for the oil and gas from the pyrolysis of industrial hemp waste is not readily available; however, some studies have been conducted on the conventional pyrolysis woody biomass (Khudyakova et al., 2018; Mohan et al., 2006). Conventionally heated fast pyrolysis of woody feedstocks can produce 60-75 wt % of liquid bio-oil, 15-25 wt % of solid char, and 10-20 wt % of non-condensable gases, depending on the feedstock used (Mohan et al., 2006). Microwave assisted pyrolysis of woody materials, without the use of microwave-absorbing additives, yields 10-35% oil and 20-30% non-condensable gas (Robinson et al., 2010); however, detailed analyses of these products is not readily available yet.

To better understand what might be possible during the microwave assisted pyrolysis of hemp waste materials, a case study using another waste material is presented:

A Case Study of Microwave Assisted Pyrolysis of Biosolids

Brodie et al. (2018) undertook a systematic study of microwave pyrolysis of biosolids (stabilised sewerage sludges) from the Euroa municipal wastewater (sewage) treatment plant (36° 46' S, 145° 33' E), with approximately 40 % moisture content. A preliminary experiment, where 80 g samples of biosolids were subjected to microwave pyrolysis in a 1.17 litre, single mode microwave chamber, was used to determine the yield of pyrolysis products and energy balance when processed at different temperatures. The chamber was fed from a variable power, 1.2 kW microwave source, operating at 2.45 GHz. The pyrolysis chamber was sealed at the top with a flanged lid that had connections to allow nitrogen gas inflow and pyrolysis gas removal. Larger samples of biosolids were treated in a 6 kW, 1 m³, multimode microwave chamber, operating at 2.45 GHz. The samples were approximately 2,500 g of biosolids, mixed with 10 % biochar as a microwave susceptor.

The amount of non-condensable syngas was calculated as the difference between dry biosolids, and the combination of the biochar and bio-oil recovered during the experiment. The resulting breakdown of pyrolysis products for both experiments was very similar, so they were pooled.

The average distribution of products by weight were biochar (59.9 %); syngas (37.7 %); and bio-oil (2.4 %). Percentages are expressed in relation to the mass of dry biosolids (Brodie et al., 2018). The biosolids, biochar and bio-oil were subjected to chemical analyses to determine nitrogen, carbon, hydrogen, sulphur, oxygen, and ash content for use in energy recovery calculations.

The yield of the different products from these experiments were: biochar (60 %), bio-oil (2 %) and syngas (38 %). The elemental composition of the bio-oil was: 4.82 % N, 73.54 % C, 9.84 % H, 0.64 % S, and 11.15 % O. The elemental composition of the biochar was: 0.7 % N, 11.8 % C, 0.0 % H, 0.5 % S, 4.37 % O, and 82.6 % Ash. This implies

that the elemental composition of the syngas was 6.67 % N, 46.71 % C, 10.8 % H, 1.89 % S, and 34.12 % O.

Almost all the products of pyrolysis can be used as fuels. The following equation was used to calculate the calorific higher heating value (HHV) of the solid materials (i.e. biosolids and biochar) (Buckley, 2010):

$$\text{HHV} = 0.3515 \cdot \text{C}\% + 1.617 \cdot \text{H}\% + 0.1232 \cdot \text{S}\% - 0.1198 \cdot (\text{O}\% + \text{N}\%) - 0.0153 \cdot \text{Ash}\% \quad (4)$$

The calorific values of the bio-oil and syngas can be determined from the Boie equation (Annamalai et al., 1987):

$$\text{HHV} = 0.3516 \cdot \text{C}\% + 1.16225 \cdot \text{H}\% - 0.11090 \cdot \text{O}\% + 0.06280 \cdot \text{N}\% + 0.10465 \cdot \text{S}\% \quad (5)$$

The HHV for the different products were Biochar = 2.34 kJ g⁻¹, Bio-oil = 36.43 kJ g⁻¹, and Syngas = 25.81 kJ g⁻¹, respectively. This translates to a recovery of 1.4 MJ per kg of processed biosolids for biochar, 0.73 MJ kg⁻¹ for the bio-oil and 9.81 MJ kg⁻¹ for the syngas. The energy required to process biosolids was approximately 7.2 MJ kg⁻¹; therefore, most of the processing energy needed for the microwave pyrolysis could be offset by the energy value of the recovered syngas, allowing for efficiency considerations for converting gas to electrical energy.

The bio-oil, recovered from the 6-kW chamber, consisted of approximately 40 % phenols and carboxylic acids; however, a total of 45 chemical compounds, from various mass spectra, have been identified in the bio-oil.

Phenols have been in production since the mid-19th century. One of the early uses for phenol was as an antiseptic. Towards the end of the 19th century, phenol was used in the synthesis of dyes, aspirin, and one of the first high explosives, picric acid. As early as 1872, it was found that phenol could be condensed with aldehydes to make resinous compounds. Phenol-methanal (formaldehyde) resins are the basis of the oldest plastics and are still used to make low-cost thermosetting plastics such as Melamine and Bakelite. These resins are also used extensively as bonding agents in manufactured wood products, such as plywood and MDF. They could also be considered for bonding agents when using hemp materials in the building industry.

The market value of phenols varies between about AU\$1.57 to AU\$1.90 kg⁻¹; therefore, the recoverable value of the phenols from one tonne of biosolids would be between AU\$12.60 and AU\$15.20. This is comparable to the fuel value of the bio-oil. Based on current prices for crude oil, which is somewhat like bio-oil, the fuel value of bio-oil would be approximately AU\$0.63 kg⁻¹ of oil or AU\$12.50 for every tonne of processed biosolids.

Some of the individual chemicals in the bio-oil have values ranging from AU\$2.20 g⁻¹ for 1,4:3,6-Dianhydro- α -D-glucopyranose to AU\$1,173.40 g⁻¹ for 2,2-Dimethoxybutane. Depending on the concentration of these chemicals in the bio-oil and the ease of extraction, the real value of the bio-oil may be in its pharmaceuticals rather than its fuel value. Further study of the chemical composition and fractional distillation of bio-oil needs to be done.

4.3 Biochar

Biochar is generally characterized by a high specific surface area, high content of surface functional groups, pH and porosity (Tomczyk et al., 2020); however, these properties vary depending on processing conditions and feedstock. Slow pyrolysis, which occurs at low to moderate temperatures (300–400 °C) and long reaction times (up to several days in a large conventionally heated system) has been practiced for thousands of years to convert wood into high yields of charcoal (biochar). In conventionally heated systems, slow pyrolysis is the most effective technique for biochar production with a typical biochar yield of 35.0% from dry biomass. Fast pyrolysis (at temperatures above 500 °C) is the most efficient method for producing biofuels and syngas (Tomczyk et al., 2020); however, low-temperature microwave-assisted pyrolysis (120–180 °C) has been found to efficiently deliver comparable products to conventionally heated pyrolysis systems, operating at much higher temperatures (250–400 °C) (Shuttleworth et al., 2012).

Operating temperature affects biochar properties. For example, Antunes, Schumann, et al. (2017) demonstrated that biochar yield (91 - 77 %) and volatile compounds within the biochar (37.7 - 25.0 %) decreased with increasing pyrolysis temperature (300 – 800 °C) during microwave-assisted pyrolysis of 63.0 ± 1 g samples of biosolids (stabilised sewerage sludge) mixed with 10 % carbon as a microwave susceptor, while ash content (55.8 - 63.3 %) and specific surface area (50.06 - 64.67 m² g⁻¹) increased with increasing pyrolysis temperature.

The time needed to reach the highest target temperature was approximately 11.9 s g⁻¹ and total processing time, including the holding time at the target temperature was approximately 25.4 s g⁻¹ (Antunes, Schumann, et al., 2017).

Heating rate also affects the properties of biochar. For example, when biosolids samples of approximately 2340 g, which were taken from the same biosolids source as used by Antunes, Schumann, et al. (2017), were processed in a 6 kW, 2.45 GHz, microwave chamber, the specific surface area increased to 75 m² g⁻¹ and the biochar was rich in mesoporosity (Bhatta Kaudal et al., 2018). This is evident from the pores with average width of 4.46 nm (Bhatta Kaudal et al., 2018).

The pyrolysis temperature in the experiment conducted by Bhatta Kaudal et al. (2018) was consistently between 600 °C and 650 °C. Processing time for this experiment, for samples with 10 % biochar added as a microwave susceptor, was approximately 1.2 s g⁻¹ (Bhatta Kaudal et al., 2018). Although the target temperature for this experiment was lower than the highest temperature in the experiment by Antunes, Schumann, et al. (2017), the heating rate was much faster, which may have contributed to the higher specific surface area for the biochar created in this experiment compared with the biochar generated in the experiment by Antunes, Schumann, et al. (2017). As Luque et al. (2012) points out, higher heating rates favour a quick release of volatiles, modifying the solid residue structure with an increased yield of the liquid and gaseous fractions.

Biochar can be used as a fuel, having an equivalent heating value to low grade coal; however, it is more commonly used as a soil amendment in agricultural and horticultural applications (Bhatta Kaudal et al., 2018; Kaudal et al., 2015). In an experiment conducted by Speratti et al. (2018), biochars were made from cotton residue, swine manure, eucalyptus sawmill residue, and sugarcane filter-cake. When the biochar was mixed with soil in pots, at 5% by weight, and maize seeds were grown, they found that cotton and swine manure biochar treatments had higher dissolved organic carbon (DOC) and NO₃- losses in the leachate from the pots than eucalyptus biochar, filter-cake biochar, and the untreated soil. Therefore, the filter-cake and eucalyptus biochars were the most promising for retaining DOC and NO₃- in a Cerrado Arenoso, potentially reducing stable C and nutrient losses (Speratti et al., 2018).

In an experiment conducted by Bhatta Kaudal et al. (2018), three plant growing media (media mixes), consisting of a) composted pine bark (80%) and sphagnum peat (20%) – a standard potting mix, b) composted pine bark (80%) and microwave generated biochar (20%), and c) composted pine bark (40%) and microwave generated biochar (60%), were tested by growing silver beet (*Beta vulgaris ssp.cicla*) as a test species. When replacing peat with 20% microwave generated biochar, there was a modest increase of shoot biomass by 37% and root biomass by 25%. Replacing peat with 60% microwave generated biochar on a volume basis, increased shoot biomass by 56% and root biomass by 50%.

In a separate experiment, Kabir et al. (2021) found that there was an optimal application of biochar, produced from the microwave assisted pyrolysis of woody waste, when using soil in a pot experiment for growing rice. A 10 % by volume application of microwave generated biochar into the soil resulted in a 23 % increase in grain yield, compared with the untreated soil; however, a 20 % by volume application of microwave generated biochar into the soil result in only a 13 % increase in grain yield, compared with the untreated soil yield. Further unpublished experiments have confirmed that there is an optimal biochar application rate when using natural soils; however, it seems that when biochar is used as part of an artificial potting mix, using more biochar in the mix seems to result in higher yields.

5. Conclusion

Most industrial processes produce a waste stream of some kind. When industrial hemp is used for fibre production, leaves, hurds, and roots are regarded as 'waste'. Although the hemp hurds can be used for various products, pyrolysis can be applied to these waste materials to render them into biochar, bio-oil, vinegars, and syngas. Microwave assisted pyrolysis is significantly faster and more efficient than conventional pyrolysis. Because dry biomass or plastic waste is relatively transparent to microwave energy, a susceptor material needs to be mixed with the waste material to better absorb the microwave energy and transfer this heat to the waste materials. Estimates of the energy requirements for microwave pyrolysis indicate that the recovered syngas could offset most of the expended energy. While the bio-oils can be used as a fuel, there are some very valuable chemicals in the bio-oils and vinegars. Therefore, depending on the recovery rates and recovery costs of these chemicals, microwave assisted pyrolysis of the waste industrial hemp waste materials could become a valuable addition to the industry. Biochar, when mixed in potting materials or

the soil, can increase agricultural productivity and capture carbon in the soil.

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