



Hydrothermal deconstruction of medicinal *Cannabis sativa* waste

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Received: 22 November 2025 / Accepted: 12 January 2026 / Published online: 2 February 2026
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Abstract

Medicinal and recreational *Cannabis sativa* is a sector that has increasing acceptance both in academia and industry due to an easing in legislation. This presents a challenge due to the legislative constraints of Δ^9 -tetrahydrocannabinol (THC), and an opportunity for sustainable management and valorisation of this waste. In this study, a mixture of organic medicinal cannabis sativa waste was processed using hydrothermal deconstruction at temperatures of 200, 250, and 300 °C for varying times of 5, 10, 15, 30, 60, and 90 min, respectively. All samples were undertaken with an initial oxygen pressure of 34 bar. Volatile fatty acids are produced throughout the reaction, with the highest total amount of 2,294 mg/L being produced at 5% initial feedstock, 300 °C, after 60 min. The amounts of acetic acid, propanoic acid, ammonia, total COD, TSS, and VSS are all highly influenced by the effects of both time and temperature, where the concentrations of phosphorus and CO₂ gas produced are primarily controlled by temperature. The product of the hydrothermal deconstruction reaction exhibits fertiliser properties, improving initial germination and plant growth by 90.0% over ten days.

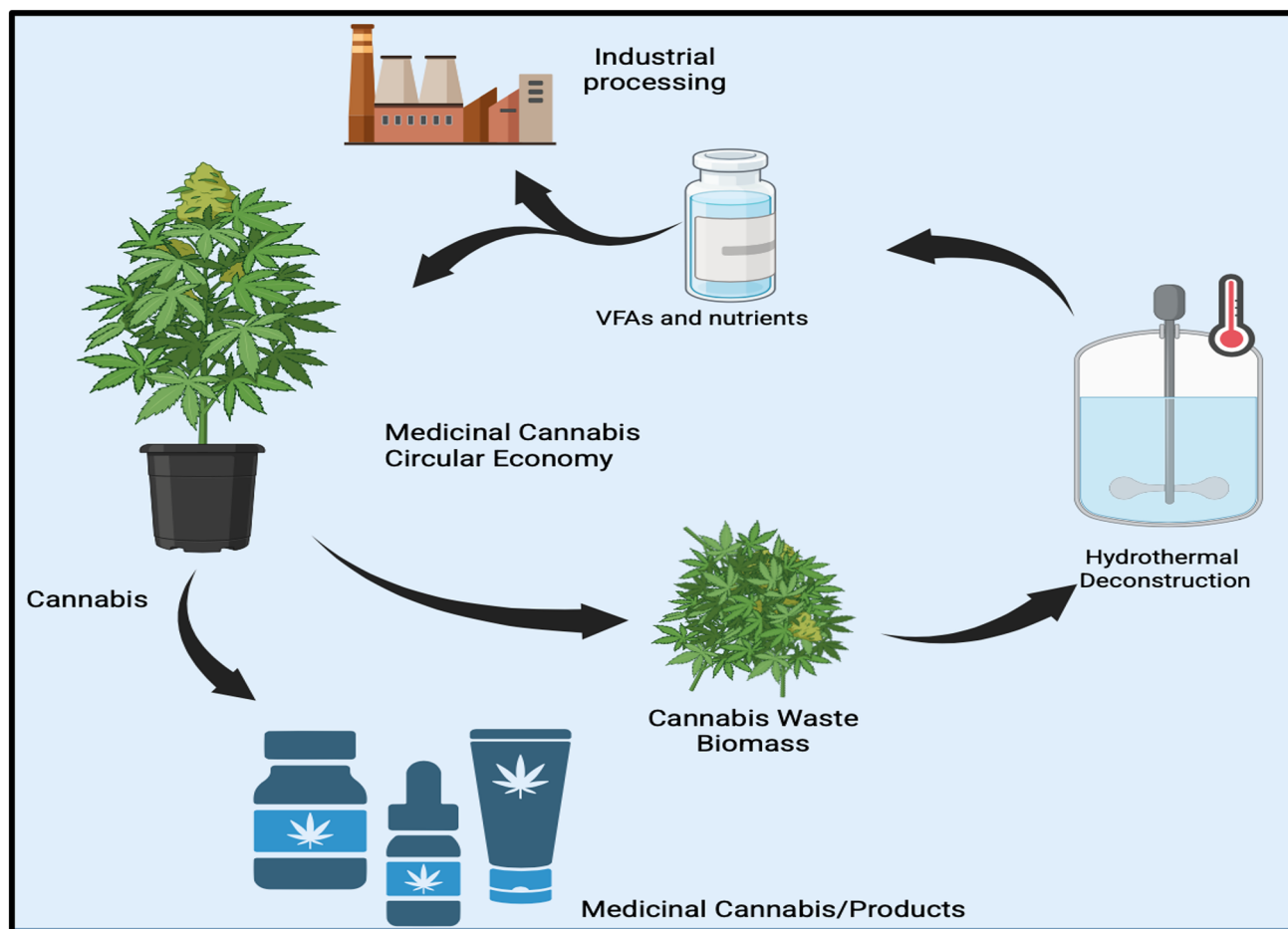
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Graphical Abstract



Keywords Medicinal cannabis · Waste treatment · Valorisation · Hydrothermal deconstruction

Introduction

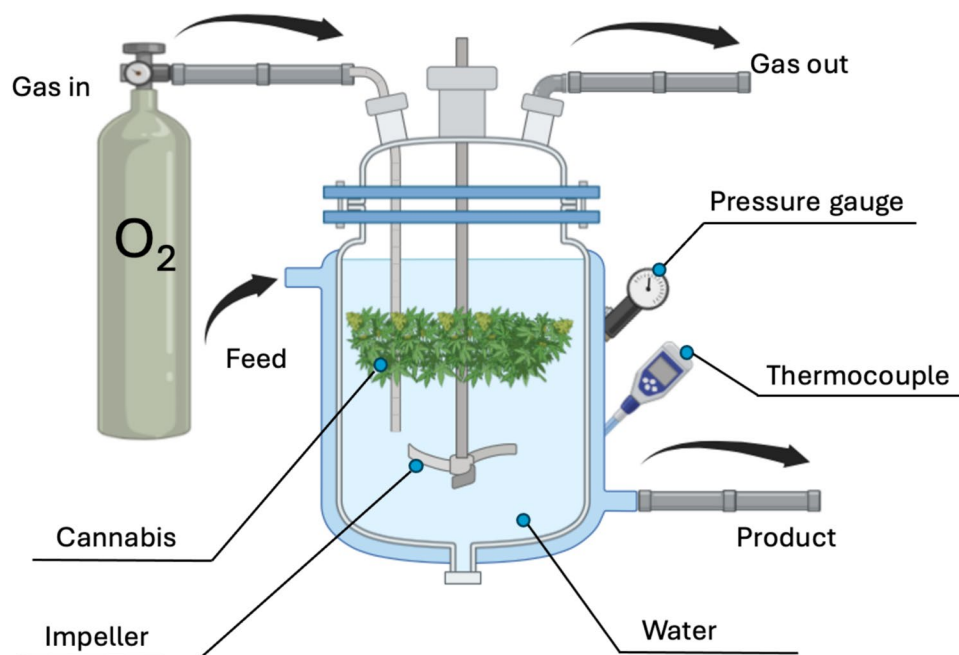
Cannabis is a plant that produces psychoactive compounds, such as tetrahydrocannabinol (THC) and cannabidiol (CBD). The therapeutic qualities of THC and CBD (Glass 2019), present mostly in the female cannabis flower (Alba 2021), are utilised to treat several medical conditions or diseases.

Over the past few decades, the societal opinion on *Cannabis sativa* and medicinal cannabis has moved forward into a more favourable light. With this increase in cannabis usage comes an increase in cultivation and production. Furthermore, the sales of cannabis products, including medicinal and recreational use, are predicted to increase from US\$37 billion in 2021 to US\$102 billion by 2026 (Prohibition Partners 2021).

This, in turn, leads to more waste generation within this industry. As only the flowers are used for medicinal

production, the rest of the plant, up to 40% of the biomass generated (Robertson et al. 2023) is waste. The THC content of this waste is in the realm of <0.03% to 2% (Jin et al. 2020). Due to the legislative conditions of cannabis waste, with the inclusion of THC and CBD, the active versions of Δ^9 -tetrahydrocannabinolic acid (THCA) and cannabidiolic acid (CBDA) (Chandra et al. 2020; Marzorati et al. 2020), an issue arises with disposal. Requirements include the waste being rendered impossible or improbable for consumption, such as in a way that prevents persons from ingesting or propagating the plant (Alba 2021). Degrading the cannabinoid content to an ineffective level can become challenging for cultivators and manufacturers, depending on the available resources and the size of their operations. However, this challenge also provides an opportunity to valorise waste into value-added products, such as volatile fatty acids (VFAs), improving yields and profits from cultivation while operating more sustainably.

Fig. 1 Configuration of the reaction vessel used for the hydrothermal deconstruction of cannabis



Hydrothermal processing is a waste valorisation method that takes organic matter as an input and can produce valuable energy and/or nutrient-dense products, valorise the waste material while minimising environmental impact. Hydrothermal processing involves either batch or continuous processing of a material in the presence of water at elevated temperatures and pressures, within the supercritical or subcritical range, in either an oxidative or non-oxidative environment. Water at these conditions displays various chemical and physical properties than at room temperature. This includes the hydrogen bonds of water becoming weaker, decreasing dielectric constant, acidity, and polarity. Because of these changes, water is then able to act as a catalyst medium for hydrothermal reactions (Biller & Ross 2016).

Hydrothermal deconstruction (HTD) is typically performed at subcritical conditions, between 150 and 350 °C (Munir et al. 2018; Robertson et al. 2023) and 10 to 750 bar (Munir et al. 2018) in an oxidative environment.

This study focuses on the properties of subjecting cannabis waste to hydrothermal deconstruction reactions under a range of differing times, temperatures, and solid feedstock percentages to determine if legislative restrictive compounds can be effectively degraded through HTD, whilst determining the optimal conditions to valorise the waste to provide the most useful products in terms of VFAs.

Hydrothermal deconstruction has been used on other biomass and organic materials, such as Tekin et al. (2022) with the deconstruction of sugar industry wastewater and

Kilgore et al. (2023) with the liquid component of wet-waste feedstocks processed through hydrothermally liquefaction reactions.

Acetic, propanoic, and butyric acids are products of HTD with multiple use cases, including food and beverage, pharmaceuticals, chemical production, solvents, flavouring, and wastewater treatment (Bhatia & Yang 2017; Zewde et al. 2023; Zigová & Šturdík, 2000). Therefore, there is an opportunity to valorise the waste into a useful product. This would be beneficial for growers and manufacturers in the industry as an additional form of economic benefit, whilst achieving the legislative requirements of managing cannabis waste.

Using the search terms “hydrothermal deconstruction” OR “wet air oxidation” AND “cannabis” on Scopus provides no documents when searched on the 23 June 2025, highlighting there is no literature available on HTD of cannabis. This work aims to contribute to the literature on different HTD conditions and results from processing cannabis using this technology; therefore, realising the benefits of this processing. It will also investigate the different parameters and characteristics of deconstructed cannabis waste.

For HTD to be a feasible and effective waste recovery process for cannabis waste, it requires complete THC and CBD deconstruction. The rationale is that if detectable amounts of THC and CBD are present in the recovered product, then it does not meet current legislation for cannabis waste management. This would mean the end result of HTD is not an effective management tool for processing medicinal cannabis waste.

Materials and methods

Materials

Cannabis waste in this study was sourced from Green Relief NZ Limited (Greenlab) in Christchurch, New Zealand. The waste consisted of unused cannabis plant biomass remaining after flower harvesting. The waste included leaves, stalks, stems, and small amounts of flowers. The waste was collected, dried, and stored in a room temperature safe at 25 °C. On the day of testing, the biomass was weighed at either 3% or 5% (weight of cannabis/weight total) as required, and ground for 105 s. The powder was then mixed with deionised water to form the test sample.

Pure oxygen gas from BOC Ltd. (New Zealand) was used for reactor pressurisation. Hach Pacific (New Zealand) high-range chemical oxygen demand test kits were used for COD analysis. Hach Pacific (New Zealand) high-range nitrogen ammonia reagent test kits were applied for $\text{NH}_3\text{-N}$. Hach Pacific (New Zealand) high-range total nitrogen test kits were used for total-N analysis. Sigma-Aldrich (New Zealand) chromatographic grade acetic acid, propionic acid, butyric acid, and valeric acid were

employed as reference standards for the calibration of volatile fatty acids (VFAs).

Hydrothermal deconstruction

The hydrothermal deconstruction (HTD) of cannabis waste was performed using a 1 L autoclave reactor (Amar Equipment Ltd, India). The reactor is equipped with an electric heater jacket, a pitched-blade turbine impeller, a thermocouple positioned in a thermowell, a Bourdon tube pressure gauge, and a pressure transducer. A PID controller was used to control the temperature and monitor the pressure of the system. The reactor configuration is illustrated in Fig. 1.

The temperature conditions, 200 to 300 °C, for HTD were chosen based on the conditions of commercial hydrothermal processes and the literature (Munir et al. 2018; Robertson et al. 2023).

The reaction time was measured from the time the interior temperature of the reactor reached the set conditions. It took approximately 15–20 min to achieve the desired internal temperatures. 550 mL of aqueous mixture of cannabis and water was added to the reactor for each run before being pressurised to 34 bar using O_2 gas.

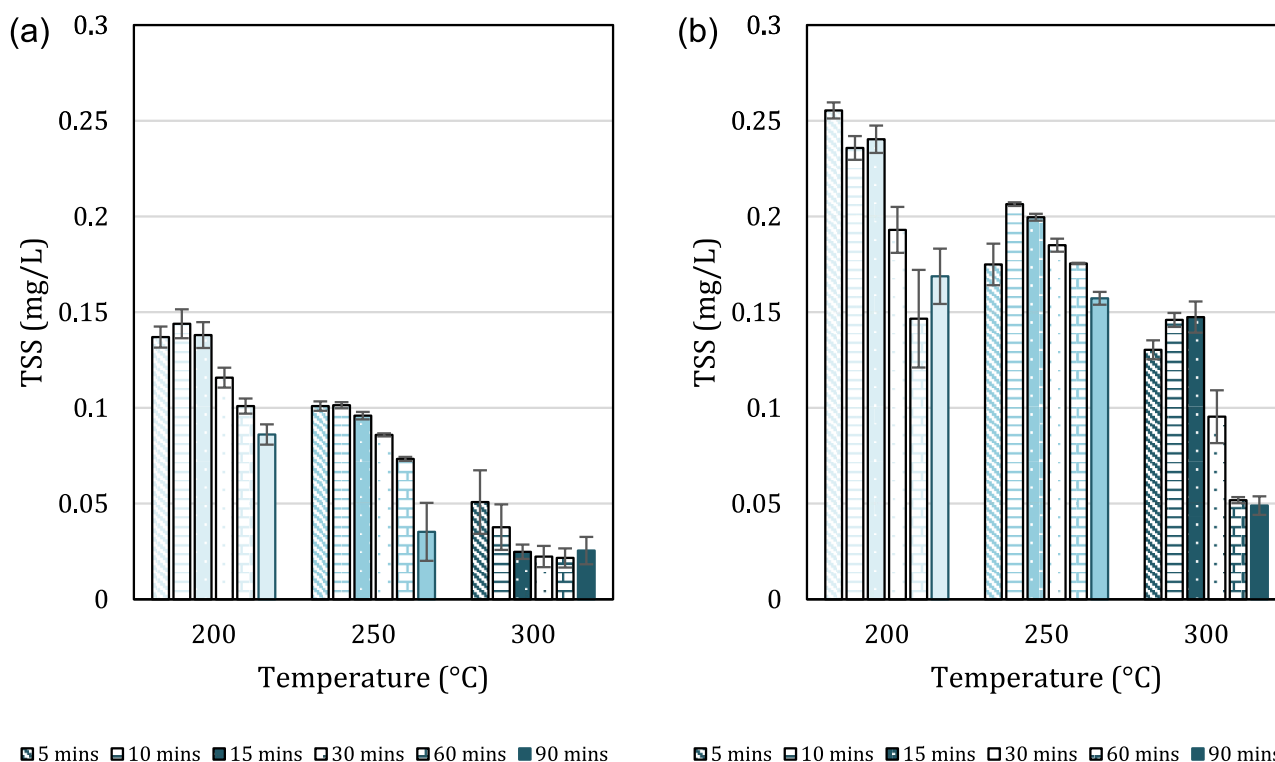


Fig. 2 TSS of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

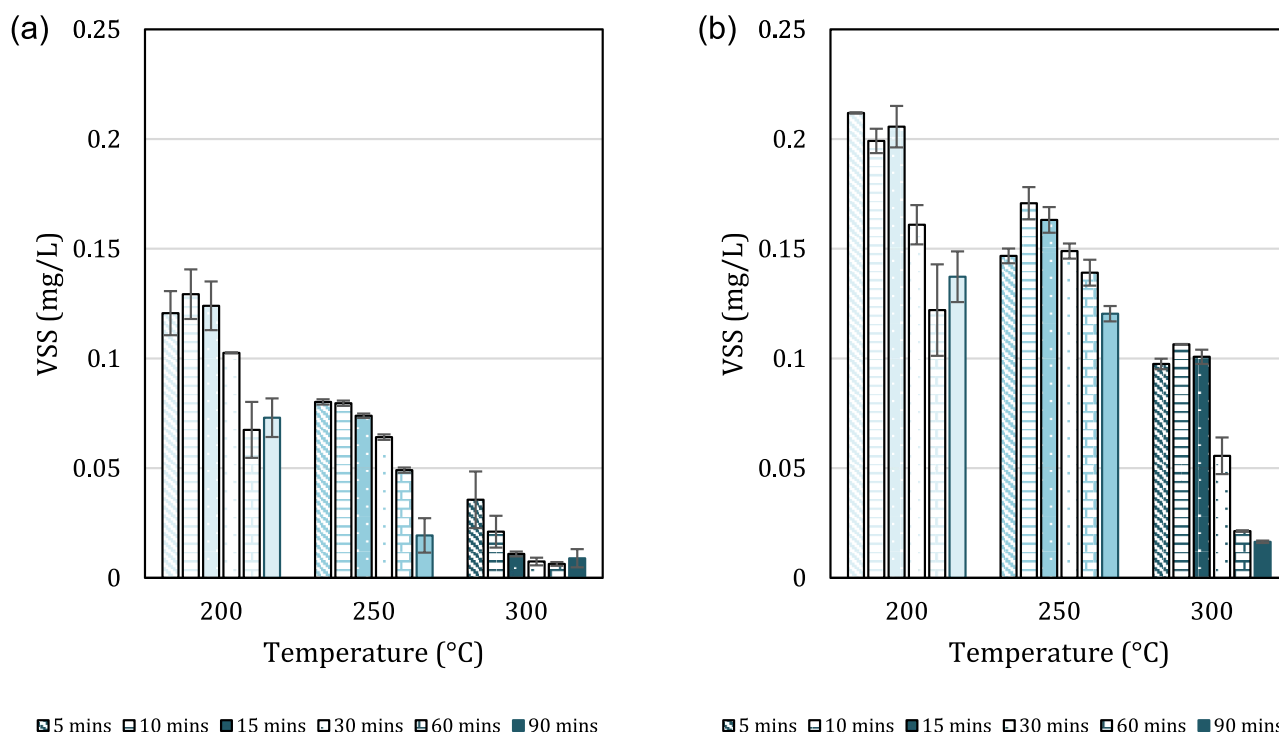


Fig. 3 VSS of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

550 mL was used when operating the reactor to account for safety considerations of liquid expansion at 300 °C whilst maximising product output. The final total pressure ranged from 15 to 80 bar, depending on the chosen temperature. The impeller mixing speed was set to stir at 300 rpm, ensuring sufficient heat transfer and mixture homogenisation. Sampling was taken at 5, 10, 15, 30, 60, and 90 min after the reactor reached temperature.

Each sample underwent vacuum filtration to remove the solid fraction, which was then placed in a 110 °C oven for 12 h, weighed, and stored, while measuring weights for TSS and VSS. The filtrate was then stored in a refrigerator set at 4 °C until testing was completed.

All conditions were run in duplicate.

Analyses

High-range COD test kits (20–1500 mg/L) from Hach (method 8000) were used to evaluate total chemical oxygen demand (tCOD) and soluble chemical oxygen demand (sCOD). The true colour of the sample was measured by a Hach DR3900 spectrophotometer using the Platinum–Cobalt method (method 8025). Similarly, the nitrogen ammonia (NH₃-N) content was evaluated using a Salicylate method (method 10,031) from Hach. A high-range test nitrogen ammonia reagent set was used for this method.

The concentration of volatile fatty acids (VFAs) in the samples was assessed by using a Shimadzu QP2010 Plus gas chromatograph (Japan) equipped with flame ionisation detection (FID). The column employed in the GC is a nitro terephthalic-acid-modified polyethylene glycol (PEG) column (DB-FFAP, 30.0×0.53×0.5 µm, Agilent Technologies, US). Helium was the carrier gas for the instrument. Initially, the column was heated to 40 °C and maintained at 40 °C for 2 min after sample injection. The temperature of the column was then increased to 180 °C at a rate of 10 °C/min, and this temperature was maintained for 26 min. The VFAs analysed were acetic, propionic, butyric, and valeric acid. The concentration was determined by calibrating reference standard solutions to sample peak retention times.

THC and CBD contents were measured first by the carboxylation of the cannabis waste and then by methanol extraction. 200 mg of leaf cuttings were ground using a commercial grinder. 20 mL of methanol was added and vortexed for 10 min (100-fold dilution), and then centrifuged at 5,000 rpm for five min. The cannabis sample was then filtered through a 4 mm, 0.45 µm syringe filter. The samples then went through HPLC analysis to determine the concentration of THC and CBD from the original cannabis waste. The HPLC analysis was conducted on one of Agilent's Zorbax Eclipse XDB columns with a C18 column reverse phase, with a mobile phase A as H₂O + 0.1% formic

acid and mobile phase B as acetonitrile + 0.1% formic acid. A PDA detector was used, with an injection volume of 10 μ L, a flow rate of 1.2 mL/min, and a detection wavelength of 220 nm.

The data were processed through generalised linear models using RStudio. Table S1 in the supplementary highlights the results produced from this analysis.

Phytotoxicity

Phytotoxicity testing was performed using a 3D-printed testing unit, in which 90 mL of Yates Hauraki Gold Peat Moss and deionised water were added until the peat reached its saturation point; in this experiment, 46 mL, with a filter paper placed on top. Ten seeds of untreated Yates Organic Tomato Black Krim were placed on top of the filter paper. The test kit with the tomato seeds was placed into a dark incubator for ten days at 25 °C. The tomatoes were opened at three, seven, and ten days to take photos of the progress of the seeds. For the sample testing, the water added was replaced with the liquid component, diluted down to ensure the liquid component added consisted of a nitrogen weight percentage of 0.0125%.

A singular dose rate was the liquid added to the soil, having a concentration of 0.0125% weight percentage of

nitrogen. Two different dose rates were examined: a single dose and a five times dose.

Results and discussion

Total suspended solids and volatile suspended solids

Total suspended solids (TSS) and volatile suspended solids (VSS) indicate the breakdown of biomass during the HTD reaction. HTD thermal degradation and oxidative environment cause the decomposition of the solid biomass, as shown in Figs. 2 and 3 with decreasing amounts of TSS and VSS for both the 3% and 5% initial feedstock percentage. TSS of the 3% feedstock starts from 0.137 mg/L at 5 min to 0.0861 mg/L at 90 min, 0.101 mg/L at 5 min to 0.0353 mg/L at 90 min and 0.0508 mg/L at 5 min to 0.0255 mg/L at 90 min for 200, 250, and 300 °C, respectively. TSS of the 5% feedstock starts from 0.255 mg/L at 5 min to 0.169 mg/L at 90 min, 0.175 mg/L at 5 min to 0.157 mg/L at 90 min and 0.130 mg/L at 5 min to 0.0490 mg/L at 90 min for 200, 250, and 300 °C, respectively. VSS of the 3% feedstock starts from 0.121 mg/L at 5 min to 0.073 mg/L at 90 min and 0.0802 mg/L at 5 min to 0.0194 mg/L at 90 min and 0.0356 mg/L at 5 min to 0.00895 mg/L at 90 min for

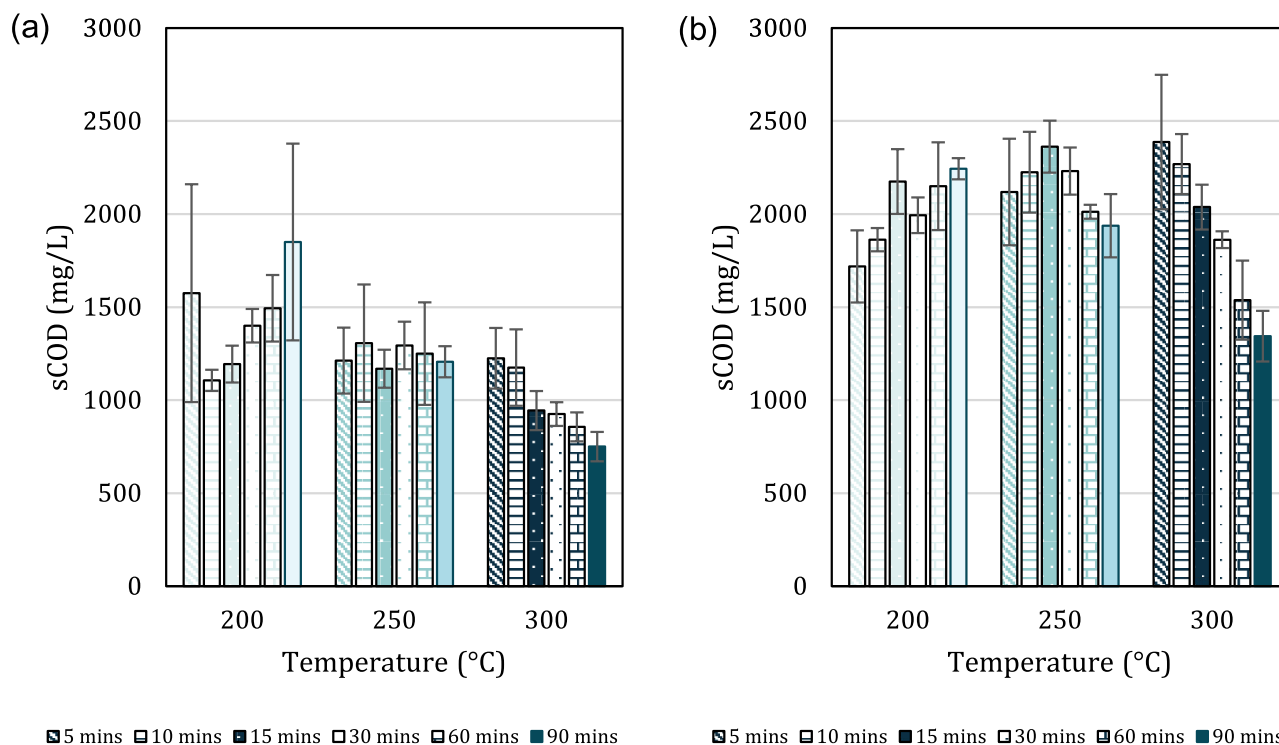


Fig. 4 Soluble chemical oxygen demand of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

200, 250, and 300 °C, respectively. VSS of the 5% feedstock starts from 0.212 mg/L at 5 min to 0.137 mg/L at 90 min, 0.147 mg/L at 5 min to 0.120 mg/L at 90 min and 0.0975 mg/L at 5 min to 0.0165 mg/L at 90 min for 200, 250, and 300 °C, respectively. When temperature or reaction time is increased, there are decreases in the amount of both TSS and VSS, highlighting the transformation and deduction of the cannabis biomass.

Debellefontaine and Foussard (2000) recommend the following five reactions to describe the HTD mechanism. Molecular oxygen reacts with the weakest of the C-H bonds (Reaction 1), and the HO_2^* radicals (Reaction 2) produce an organic radical. The reaction is then initiated by the organic radical through a reaction with oxygen molecules (Reaction 3). Due to the elevated temperature, the hydrogen peroxide produced is decomposed rapidly into hydroxyl radicals (Reaction 4). Reaction 5 is a propagation step leading to species becoming oxidised, as the hydroxyl radical is a strong oxidation agent (Zou et al. 2007).



From these reactions, oxygen and biomass are being deconstructed, converting into carboxylic acids, with acetic acid being the most common of these, which is produced during HTD.

Exhibited in both initial feedstocks, there is an increase in TSS and VSS at the initial times, which is likely attributed to the hydrolysis phase still breaking down and dissolving the biomass.

The amount of TSS and VSS produced from all of the 5% feedstock is greater than that of the 3% feedstock. This can be attributed to the greater amount of initial solids in the reaction, resulting in a higher concentration of solids at the end of the reaction.

HTD can convert the organic biomass into carbon dioxide through Eq. 6 (Zou et al. 2007).



This reaction highlights the generation of carbon dioxide from the decomposition of cannabis.

biomass. Further discussion on the transformation of biomass to carbon dioxide is in Sect. “Gaseous products”.

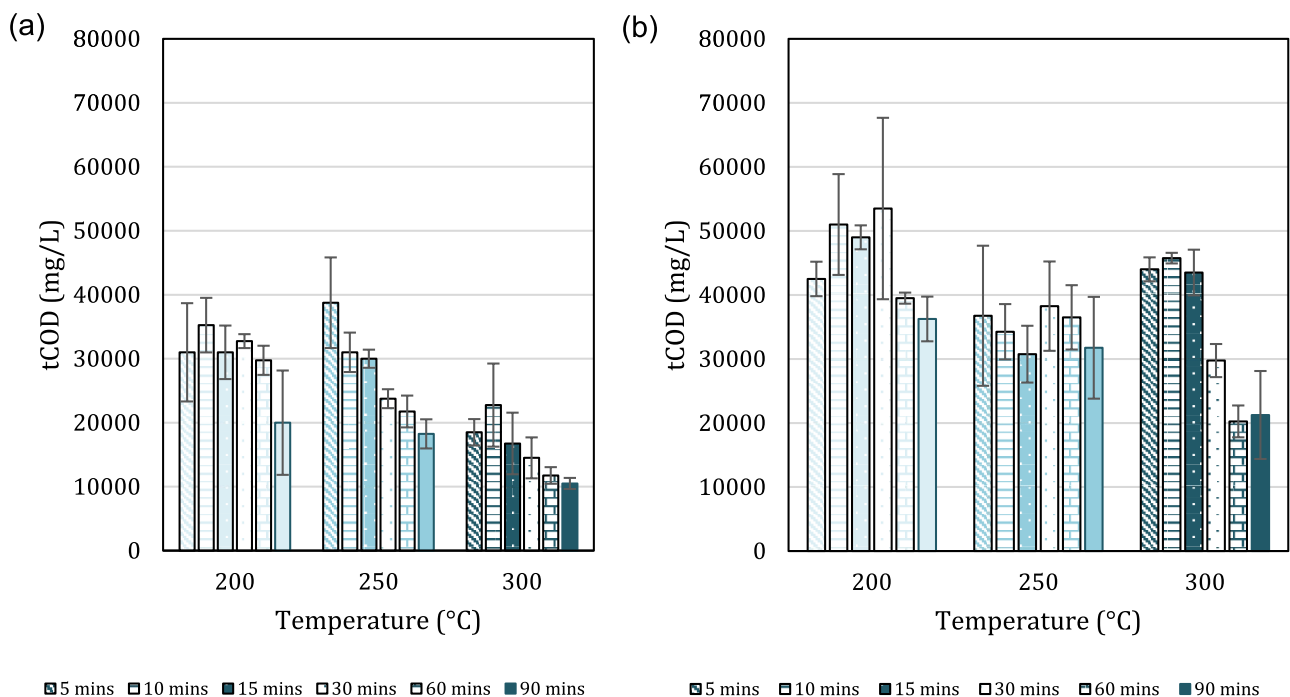


Fig. 5 Total chemical oxygen demand of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

Strong et al. (2011) found, while using municipal biosolids, a VSS reduction of 93% and TSS reduction of 83%, whereas this study finds reductions of up to 83.1% for VSS and 65.1% for TSS from 5 to 90 min of reaction.

Statistical analysis was conducted to evaluate the effect of temperature and time on the HTD reaction, as well as on TSS, VSS, and all other parameters measured during this study. When comparing the effects of time on the TSS and VSS, p values of 1.28×10^{-8} and 7.85×10^{-9} for 3% feedstock and 2.37×10^{-7} and 5.89×10^{-8} for 5% feedstock were obtained, respectively. These p values indicate a highly significant effect on the results of TSS and VSS based on the time of the HTD reaction. The effect of temperature resulted in p values for TSS and VSS of 1.17×10^{-17} and 2.18×10^{-17} for 3% feedstock and 4.57×10^{-11} and 6.37×10^{-13} for 5% feedstock, indicating, similar to the time of the reaction, that there is a significant effect of temperature on the TSS and VSS values.

THC and CBD degradation

When conducting testing of products from HTD, the THC and CBD content were also analysed. The starting cannabis material has a THC content of 0.27 ± 0.039 w/w% ($2.7 \text{ mg/g} \pm 0.39 \text{ mg/g}$) and a CBD content of 0.058 ± 0.027 w/w% ($0.58 \text{ mg/g} \pm 0.27 \text{ mg/g}$). This is consistent with

the amount of cannabinoids present in the cannabis leaves (1–2%) and stems (0.1–0.3%) (Jin et al. 2020). As this cannabis mixture is a combination of these different aspects of the plant, the amount of these cannabinoids present is expected.

It was found that throughout all testing parameters, including the lowest temperature and time of 200 °C and 5 min, THC and CBD were deconstructed, with no detectable amounts found in any of the products. The limit of detection for both THC and CBD was calculated to be 3.14×10^{-6} weight percentage of the sample. An example of the chromatography result is shown in Figure S1.

The likely pathway for the deconstruction of Δ^9 -THC to Δ^8 -THC to CBN (García-Valverde et al. 2022). The likely pathway for CBD reacting in this reaction is to then go to Δ^9 -THC to Δ^8 -THC to CBN (García-Valverde et al. 2022).

Soluble and total chemical oxygen demand

Chemical oxygen demand (COD) is a measure of the amount of oxygen required to completely oxidise all organic molecules within the solution. For this reason, COD can be used as a replacement for organic material, as an increase or decrease in COD indicates an increase or decrease, respectively, in the amount of organic matter

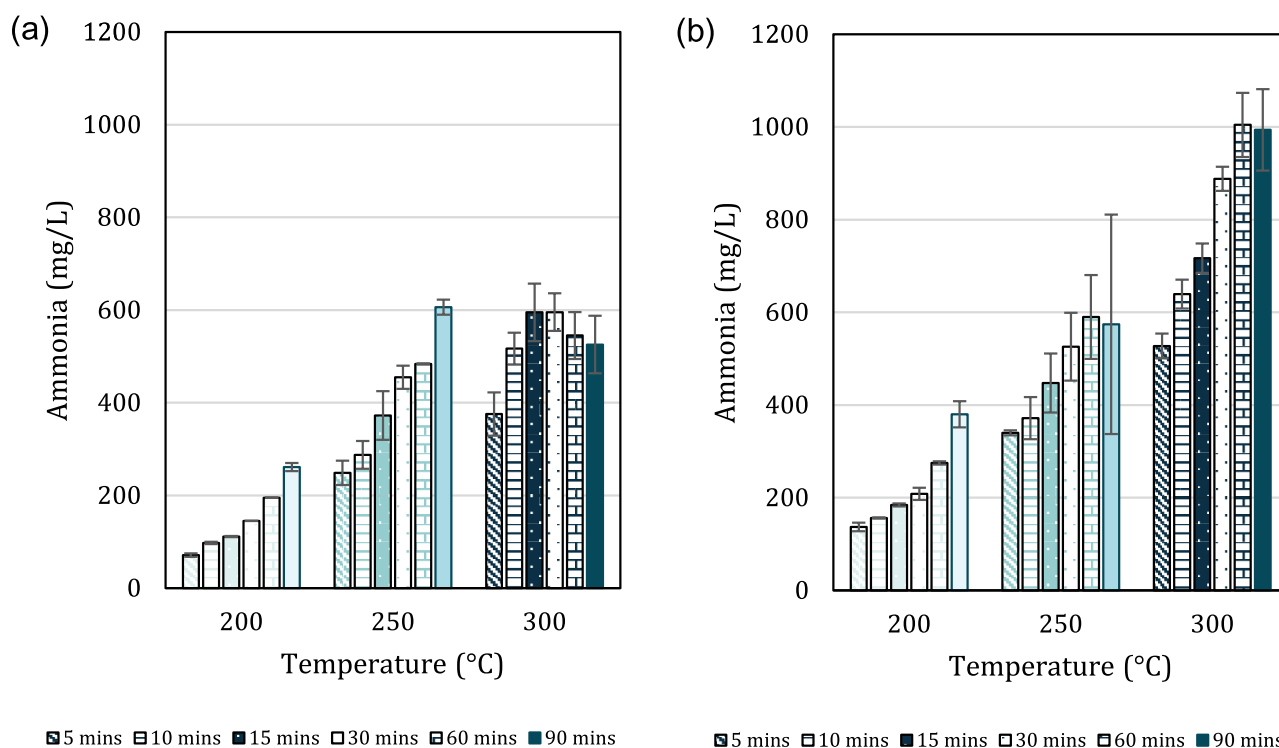


Fig. 6 Ammonia concentration of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

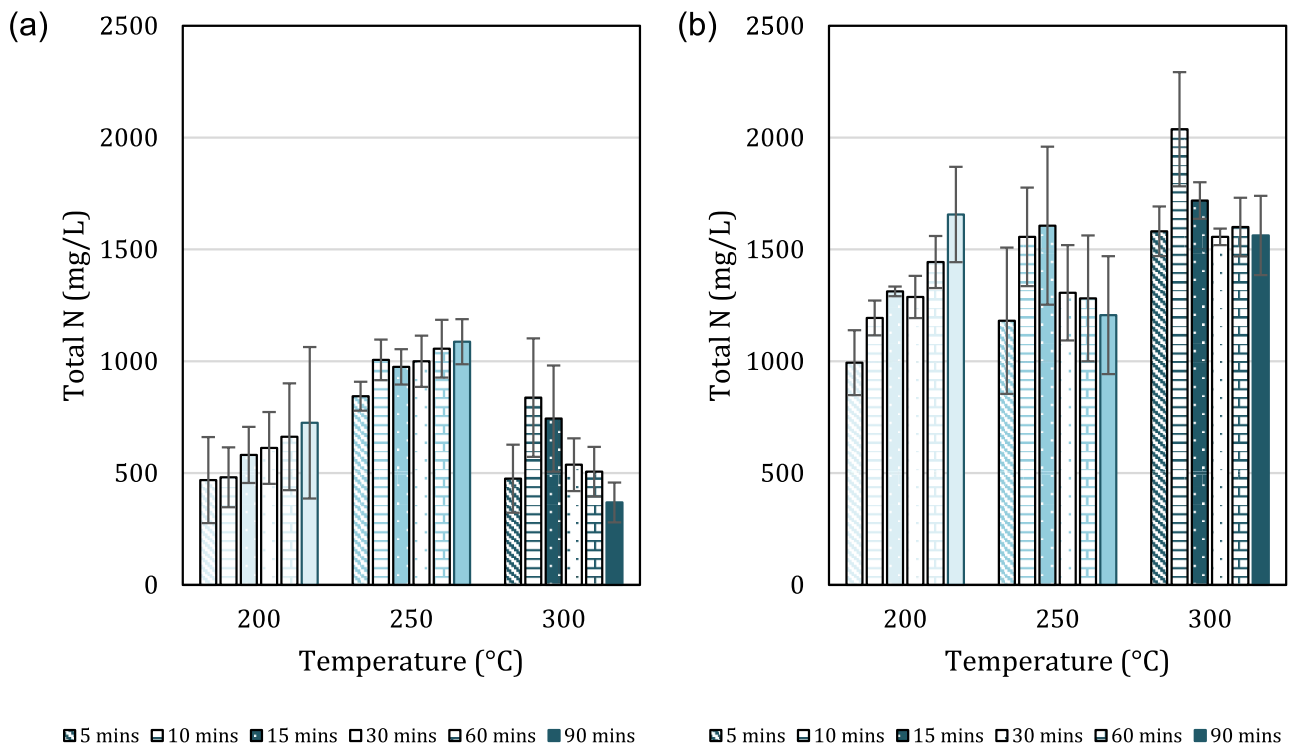


Fig. 7 Total nitrogen concentration of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

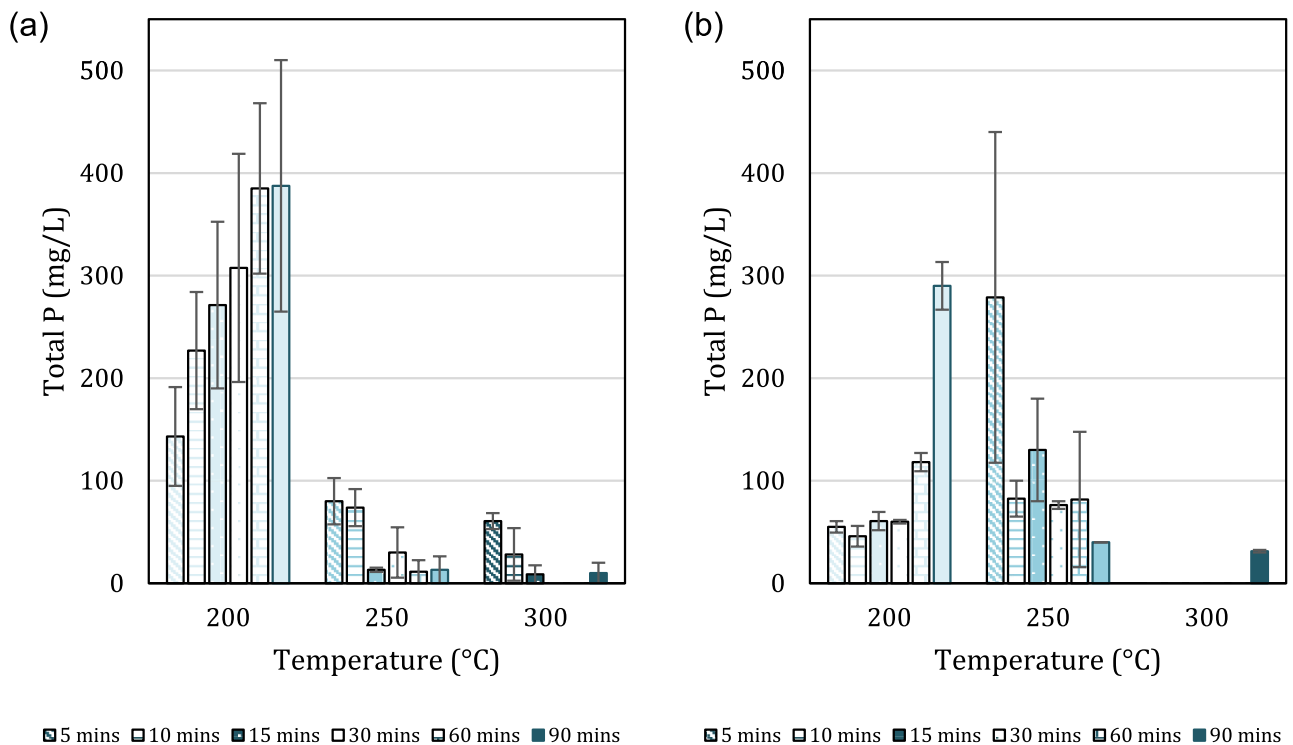


Fig. 8 Phosphorus concentration of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

in solution. Similar mechanistic properties are observed for COD, as indicated by the decreases in TSS and VSS.

When examining Fig. 4, there is an initial increase in soluble chemical oxygen demand (sCOD) at 200 °C at the time ranges of 5 min to 90 min, with these amounts then decreasing. During the hydrolysis stage of HTD, the biomass is broken down and dissolved within the water; the reason for this initial increase is that the biomass is still being dissolved. For 300 °C, sCOD consistently decreases from 1,225 mg/L, at 5 min, to 750 mg/L, at 90 min, for 3% feedstock, whilst 5% feedstock decreases from 2,388 mg/L, at 5 min, to 1,344 mg/L, at 90 min, indicating that the soluble organic biomass is transforming throughout the HTD reaction.

When examining Fig. 5 the total chemical oxygen demand (tCOD) is decreasing with increasing temperature and time, from 31,000 mg/L at 5 min to 20,000 mg/L at 90 min, 38,750 mg/L at 5 min to 18,250 mg/L at 90 min and 18,250 mg/L at 5 min to 10,500 mg/L at 90 min for 200, 250 and 300 °C, respectively, for 3% feedstock and 42,500 mg/L at 5 min to 36,250 mg/L at 90 min, 36,750 mg/L at 5 min to 31,750 mg/L at 90 min and 44,000 mg/L at 5 min to 21,250 mg/L at 90 min for 200, 250, and 300 °C, respectively, for 5% feedstock. Similar to sCOD, this illustrates the organic biomass being deconstructed and converted into other products. The tCOD does not exhibit the initial increase that the sCOD does; this is due to the tCOD including non-dissolved biomass, unlike the sCOD.

When comparing the sCOD and tCOD between the 3% and 5% initial feedstock, it is noted that the 5% feedstock has higher values at all temperatures and times. It can be concluded that a larger amount of biomass going into the reaction would require further processing and oxidation of the components than a lower biomass feedstock.

Brunner (2014a) highlights that COD decreases as the HTD reaction continues, noting that the reduction of COD from organic matter is generally below 95%. Brunner (2014b) notes that HTD can be used as a water cleaning method by reducing COD of the feed down to suitable discharge levels.

Completing statistical analysis on the effect of time of the HTD reaction on sCOD produces *p* values of 0.819 for 3% feedstock and 0.0300 for 5% feedstock. These *p* values indicate that there is weak significance for 5% feedstock and no significance for the 3% feedstock. As for the effect on temperature, *p* values of 4.70×10^{-5} for 3% feedstock and 0.335 for 5% feedstock. From all these different *p* values, it is evident that there is some significance in the effect of time and temperature on the sCOD of the products, but inconsistencies remain. The effect of the delayed dissolving of biomass completely into solution would lead to skewing the results, as the samples of the earlier time tested would not have the

full biomass dissolved and, as a result, would have lower sCOD values than would be expected. Analysing tCOD *p* values for time shows a highly significant effect of tCOD with values of 5.94×10^{-7} for 3% feedstock and 4.61×10^{-4} for 5% feedstock. For temperatures, the effect on tCOD *p* values of 5.77×10^{-9} for 3% feedstock and 0.00108 for 5% feedstock is present, which, similar to the influence time has on tCOD, shows there is a significant effect of temperature on tCOD from the reaction. This is expected, as with an increase in time and temperature of the HTD reaction, the tCOD, serving as a replacement for biomass, is expected to decrease as the biomass is oxidised and broken down into smaller organic molecules.

Ammonia, total nitrogen and total phosphorus

Nitrogen and phosphorus are essential building blocks of plant life. When applying fertilisers or soil amendment products, it is vital to know the amounts of nitrogen and phosphorus to tailor the fertiliser for the plant. Measuring these elements from cannabis treated through HTD processing will give insight into the reaction mechanisms that occur throughout HTD and will allow for improved reaction planning for the production of fertiliser from this method.

When examining Fig. 6, it is displayed that there is a general increase in the amount of ammonia produced from the HTD reaction. With the 3% feedstock, at 200 °C, there is a gradual increase from 71.2 mg/L at 5 min to 261 mg/L at 90 min, and at 250 °C, there is 249 mg/L at 5 min, which increases to 606 mg/L at 90 min. For the 5% feedstock, there are increases from 137 mg/L at 5 min to 380 mg/L at 90 min, 340 mg/L at 5 min to 574 mg/L at 90 min and 528 mg/L at 5 min to 994 mg/L at 90 min for 200, 250, and 300 °C, respectively. All of the ammonia values from the 5% feedstock are greater than those of the 3% feedstock; this is expected as more biomass within the reactants would produce more products from the reaction. Ammonia is generally formed as a by-product of the oxidation of nitrogen from the organic compounds, whereas carbon is oxidised into carbon dioxide, and nitrogen is also found in the NH_4^+ form.

Figure 7 shows the total amount of nitrogen present within the products of the hydrothermally deconstructed cannabis biomass. The total amount of nitrogen fluctuates with increasing temperature and reaction time. With the 3% feedstock, the amount of nitrogen in solution starts at a low of 469 mg/L, at 5 min and 200 °C, which increases by 132% to a maximum of 1,088 mg/L, at 90 min and 250 °C. The 3% feedstock then decreases at 300 °C to a minimum of 369 mg/L. The 5% feedstock increases from 994 mg/L, at 5 min, to 1,656 mg/L, at 90 min, for 200 °C. For 5% feedstock, total nitrogen fluctuates between 1,181 mg/L and 1,606 mg/L, for 250 °C, and 1,562 mg/L and 2,038 mg/L, for 300 °C.

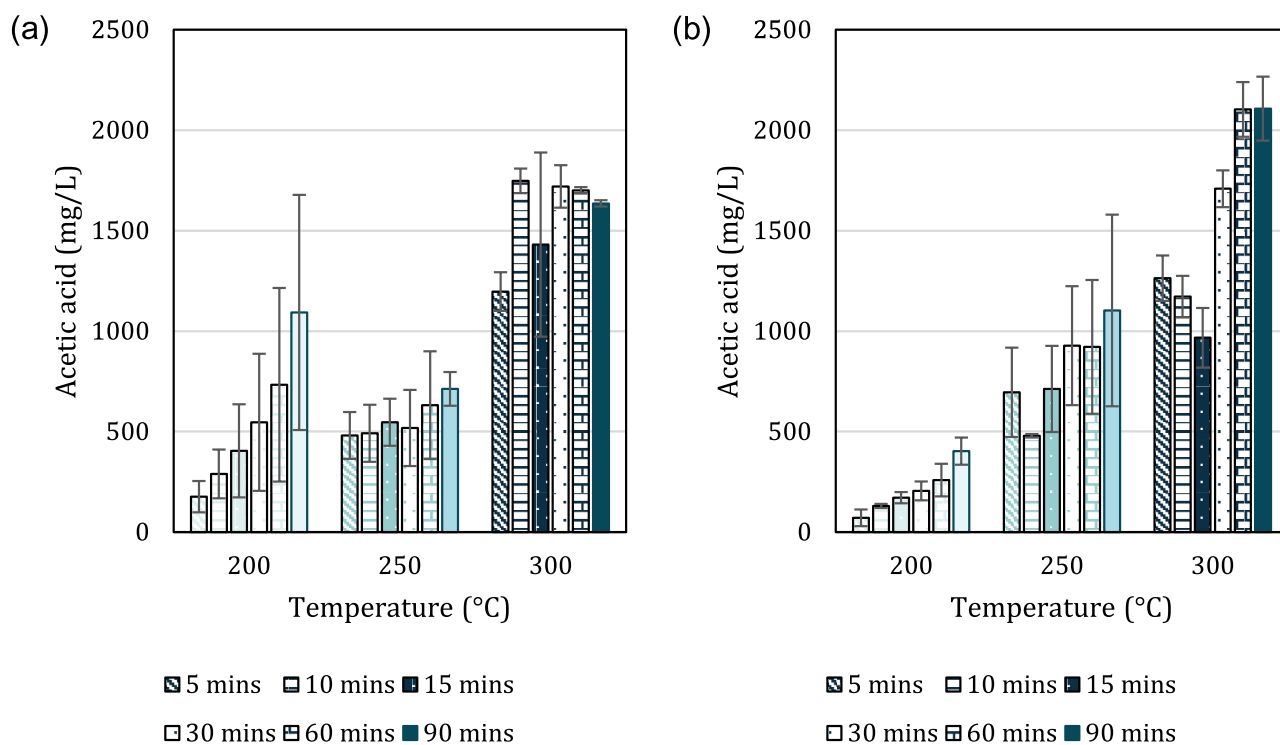


Fig. 9 Acetic acid concentration of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

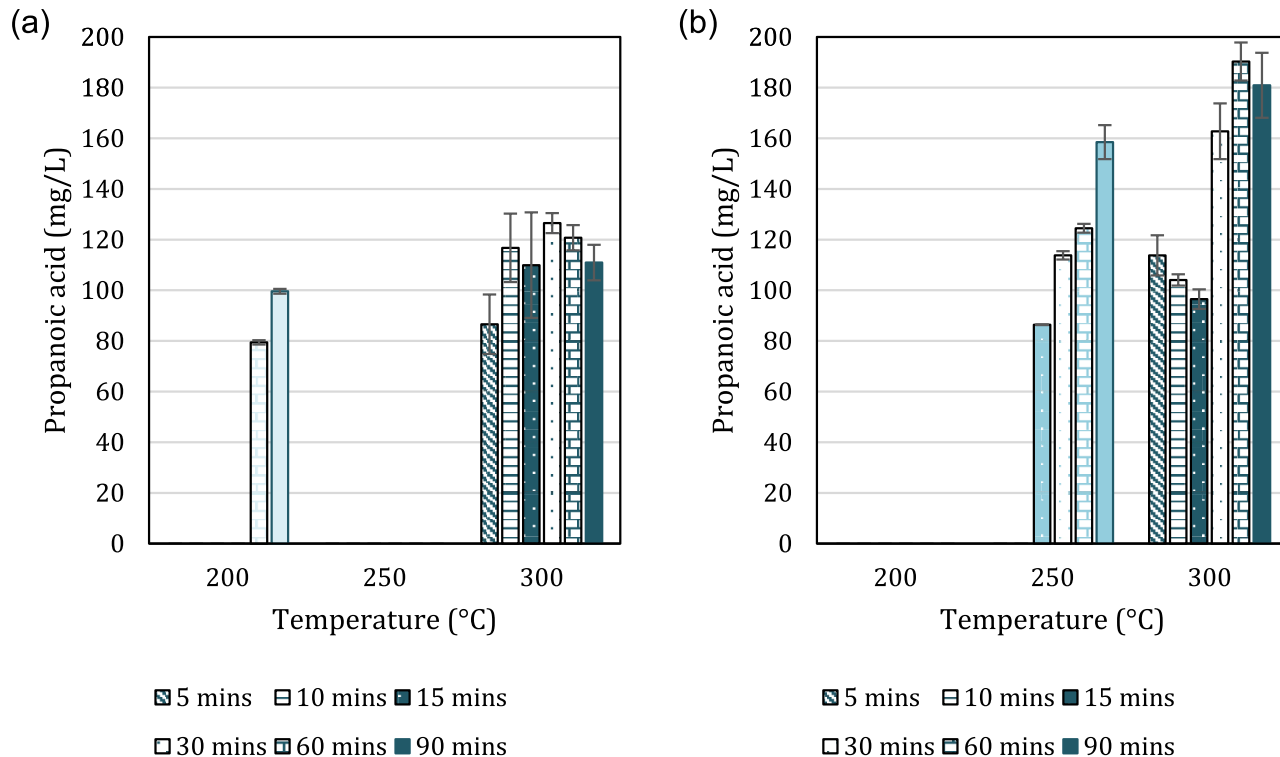


Fig. 10 Propanoic acid concentration of hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock; **b** 5% solid content feedstock

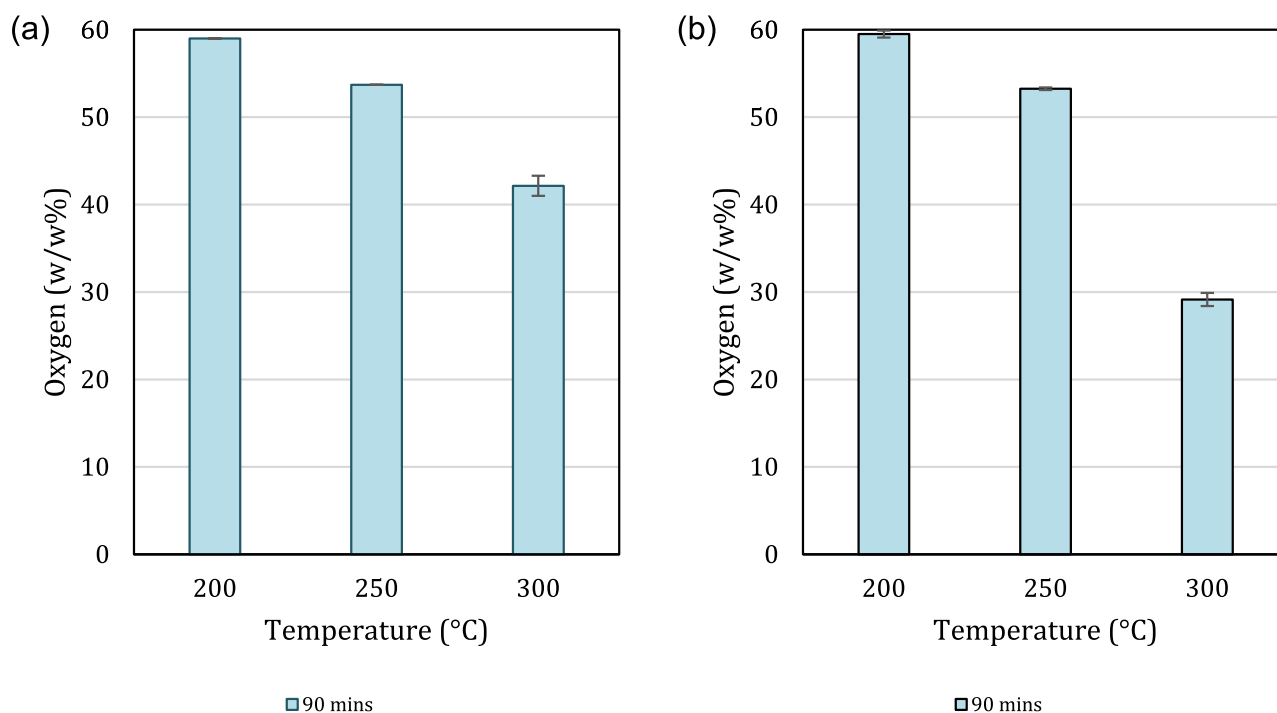


Fig. 11 Oxygen off gas from hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock and **b** 5% solid content feedstock

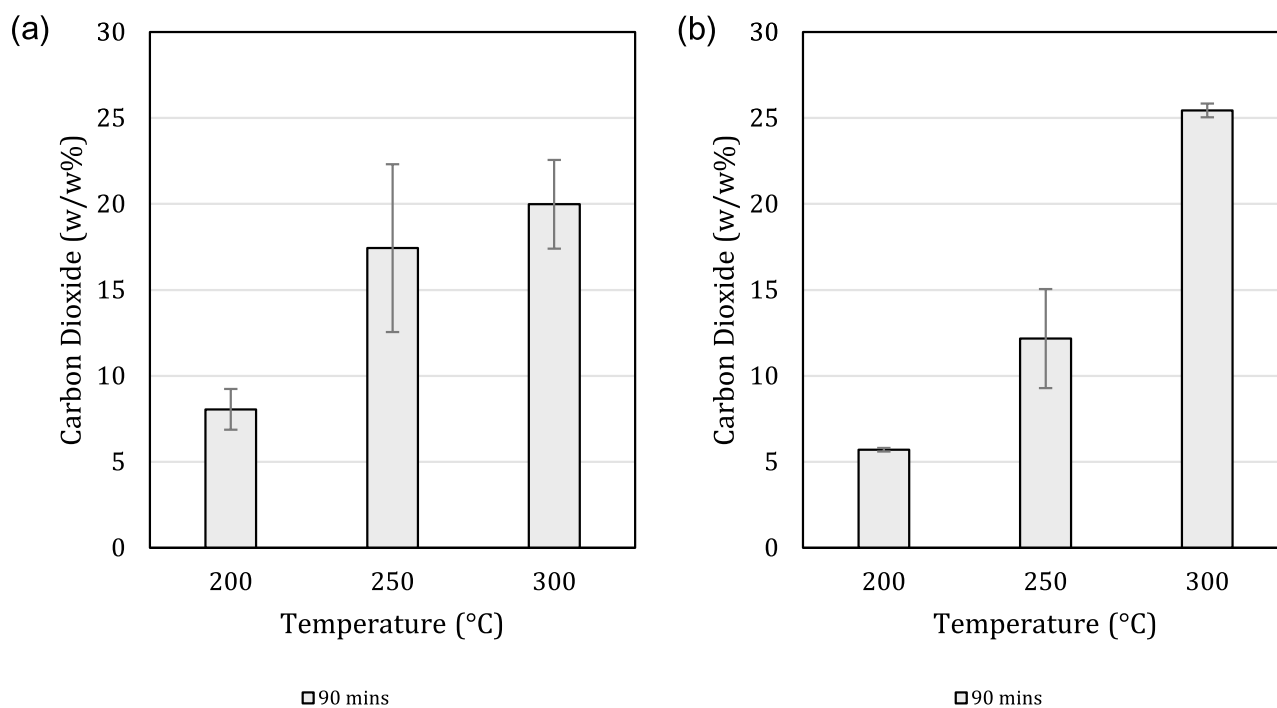


Fig. 12 Carbon dioxide off gas from hydrothermally deconstructed cannabis waste under different reaction time and temperature conditions: **a** 3% solid content feedstock and **b** 5% solid content feedstock

The solubilisation of nitrogen from the biomass would increase the amount of total nitrogen within the solution; then, as the proteins and components of the cannabis biomass become deconstructed further, nitrogen is available within the solution. Finally, when the temperature and times of the HTD reaction are prolonged, nitrogen can then become oxidised to N_2 gas, leaving the solution and decreasing the total nitrogen amounts within the solution (Qin & Aika 1998; Silva Thomsen et al. 2024).

Total phosphorus is shown in Fig. 8, where for 3 and 5% feedstock, at 200 °C, this measure increases from 143 mg/L and 55 mg/L, at 5 min, to 388 mg/L and 290 mg/L, at 90 min, respectively. At 250 °C, phosphorus decreases from 80 mg/L to 13 mg/L for 3% feedstock and 279 mg/L to 40 mg/L for 5% feedstock. Phosphorus content in 300 °C was either minimal, compared to 200 and 250 °C, or there was no detectable value.

Completing statistical analysis on the effect of time on ammonia produced from HTD, p values of 0.00309 for 3% feedstock and 6.11×10^{-6} for 5% feedstock are produced. For the effect of temperature on the amount of ammonia produced, p values of 3.15×10^{-12} for 3% feedstock and 3.46×10^{-14} for 5% feedstock are produced. These values stipulate that the amount of ammonia produced from this reaction is highly controlled based on the time and temperature used for the HTD reaction. As for total nitrogen, p values for time are 0.786 for the 3% feedstock and 0.826 for the 5% feedstock, indicating little significance in the total amount of nitrogen in solution based on the reaction time. The effect of temperature on total nitrogen in solution results in p values of 0.929 for 3% feedstock and 0.00312 for 5% feedstock. There seems to be a slight significance in the temperature on total nitrogen for 5% feedstock, but

no significance for the 3% feedstock. The effect of time on the total phosphorus in solution is not significant, with p values generated of 0.327 for 3% feedstock and 0.410 for 5% feedstock. The effect of temperature on the total amount of phosphorus indicates a significant effect, with p values of 8.36×10^{-8} for 3% feedstock and 0.00871 for 5% feedstock, showing there is control based on the temperature of the reaction to determine the amount of phosphorus within the solution of products.

Total phosphorus decreases in the liquid component of the product from the deconstruction of cannabis as the temperature increases, with 300 °C containing undetectable limits. The cause of this is likely to be attributed to the phosphorus available, contributing to the hydrocar formation and removed when the solid component is filtered from the solution, which is consistent with Zhi et al. (2024)'s work with sewage sludge where phosphate recovery in solid components of thermally processed products is greater at increased temperatures.

Volatile fatty acids in liquid component

The four VFAs measured in each liquid component sample are acetic acid, propionic acid, butyric acid, and valeric acid. These are the four most common VFAs produced from the HTD reaction, with acetic acid being the VFA that is produced in the highest quantities. VFAs are a valuable product that can be collected from the HTD process, as they are used in various industries, including pharmaceuticals, biodegradable plastics, and biofuels. VFAs can be a valuable product that can be an additional income stream for production.

When examining Fig. 9, it is displayed that there is a general increase in the amount of acetic acid produced from the

Fig. 13 Phytotoxicity test conditions at day 0, initial set up (a) and Phytotoxicity testing day 10 results for control samples, peat and water (b)

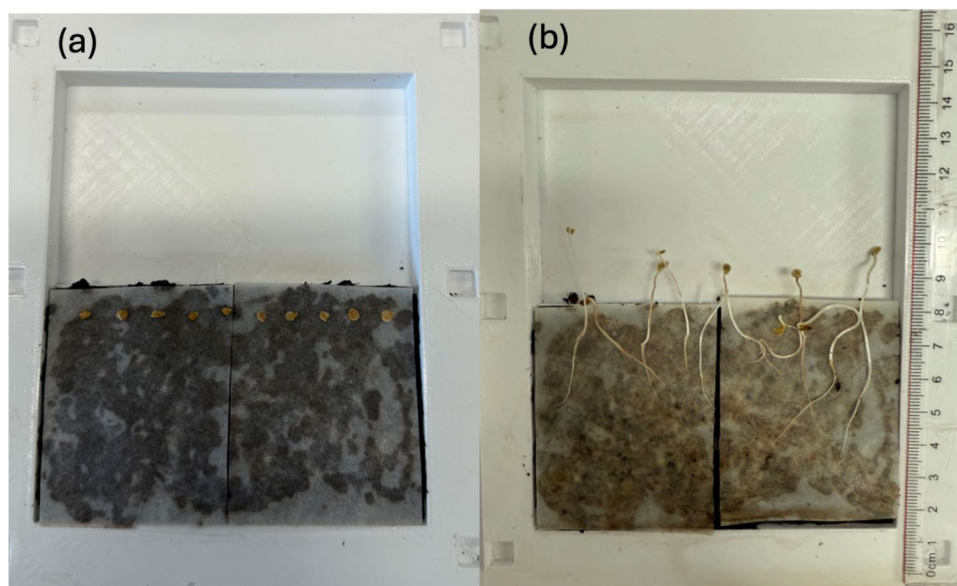
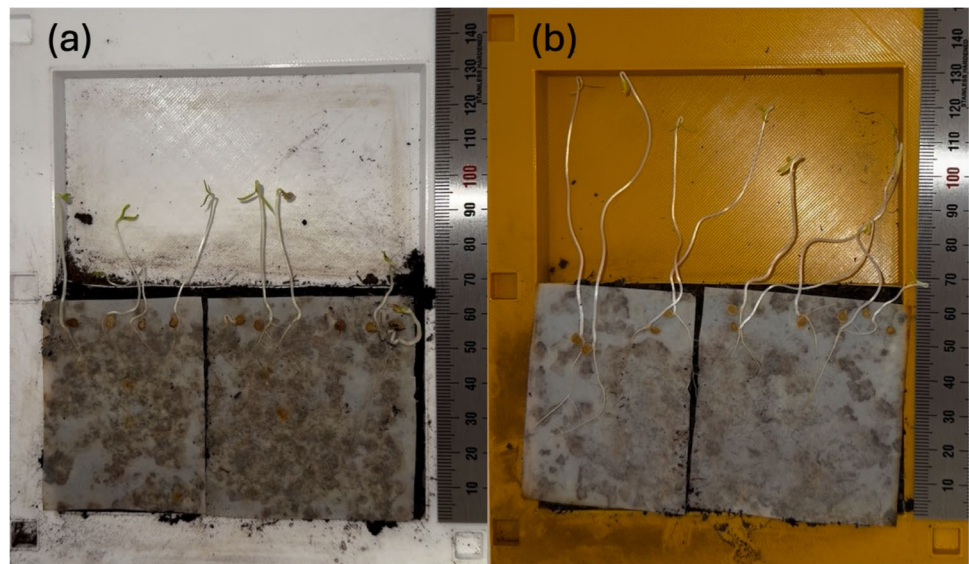


Fig. 14 Phytotoxicity test results of HTD liquid at day 10 for **a** one times dose and **b** five times dose



HTD reaction with increasing time. With the 3% feedstock, at 200 °C, there is a gradual increase from 176 mg/L at 5 min to 1,093 mg/L at 90 min, at 250 °C, there is 481 mg/L at 5 min, which increases to 712 mg/L at 90 min, and at 300 °C there is 1,197 mg/L at 5 min, which increases to 1,636 mg/L at 90 min. For the 5% feedstock, there are increases from 71 mg/L at 5 min to 403 mg/L at 90 min, 695 mg/L at 5 min to 1,103 mg/L at 90 min and 1,263 mg/L at 5 min to 2,107 mg/L at 90 min for 200 °C, 250 °C and 300 °C, respectively. As the time and temperature of the HTD reaction increase, the amount of acetic acid produced also increases.

When observing Fig. 10, there are many conditions in which there were no observable concentrations of propanoic acid, mainly at 200 and 250 °C. For the 3% feedstock, values at 300 °C range between 86.6 mg/L and 126.5 mg/L. For the 5% feedstock of the observable data, there are increases in concentration with time at 250 °C, from 86.4 mg/L at 15 min to 158.5 mg/L at 90 min. There is also an increase with 5% feedstock at 300 °C, from 96.5 mg/L at 15 min to 190.3 mg/L at 60 min.

There were no detectable quantities of butyric acid and valeric acid found in samples of any time and temperature.

During HTD, the longer molecules from the biomass are oxidised into various intermediate products. Most of the initial intermediary products formed, apart from low-chain carboxylic acids, are unstable and are oxidised further to various end products, such as CO₂, or to low-chain carboxylic acids, predominantly acetic acid (Mishra et al. 1995; Padoley et al. 2012).

Statistical analysis was conducted to investigate the effect of temperature and time on the HTD reaction, specifically on the generation of acetic and propanoic acid. When comparing the effects of time on the acetic and propanoic acid

generation, *p*-values of 2.48×10^{-4} and 0.0124 for 3% feedstock and 2.92×10^{-9} and 1.86×10^{-4} for 5% feedstock, respectively. These *p* values indicate that there is a very significant effect on the generation of acetic and propanoic acid based on the time of the HTD reaction. The effect of temperature resulted in *p* values for acetic and propanoic acid generation of 6.60×10^{-14} and 9.00×10^{-14} for 3% feedstock and 3.14×10^{-26} and 3.33×10^{-19} for 5% feedstock, respectively, indicating, similar to the time of the reaction, that there is a significant effect of temperature on the generation of acetic and propanoic acid.

The highest amount of total VFAs produced, acetic and propanoic acid, is at 300 °C at 60 min.

Gaseous products

The gaseous product at the end of the 90-min reactions was analysed for O₂ and CO₂, as shown in Figs. 11 and 12, respectively. It is observed that both 3 and 5% initial feedstock decreases in the amount of O₂ and increases in CO₂ as temperature increases. The increase in temperature and energy would not only increase the rate at which the HTD reaction occurs but also provide sufficient energy to overcome the activation energy of the different reactions required to deconstruct the biomass. As O₂ is a reactant in the HTD reaction, the decrease in O₂ as a percentage of the gaseous environment would be expected as the reaction progresses.

Zhang (2020) notes that the development of CO₂ is from the breaking of C–C bonds from free radicals attacking the organic matter and from REDOX reaction mechanisms, which are then oxidised into either acetic acid, which is oxidised into final reactants, or is oxidised straight into final reactants. Reactions 7 and 8 indicate the mechanisms

following the modular model of products from the HTD reaction (Zhang 2020).



where

A = initial land unstable intermediate organic compound bonded to acetic acid.

B = Acetic acid.

C = Oxidated final product, CO₂ and H₂O.

With CO₂ being one of the final products from this mechanistic model, it is expected that CO₂ would be produced throughout the HTD reaction, highlighting the increase in CO₂ as the temperature is increased.

Completing statistical analysis on the effect of temperature on the amount of O₂ left in the reactor, *p* values of 1.01×10^{-22} for 3% feedstock and 9.77×10^{-18} are generated, indicating a very significant effect of the temperature on the amount of O₂ left within the reactor. For the effect of temperature on CO₂ generated throughout the reaction, *p* values of 7.36×10^{-9} for 3% feedstock and 5.72×10^{-20} for 5% feedstock are generated, indicating a very significant effect of temperature on the amount of CO₂ generated from the HTD reaction.

It is likely that other gases, such as CH₄, CO, and H₂, could also be present; however, these gases were found to be negligible compared to CO₂ and O₂ and could not be consistently and accurately measured with the available equipment.

Phytotoxicity

The samples of the HTD process contain valuable nutrients that can be utilised as a fertiliser. Phytotoxicity testing was completed on these samples. Included in this test was the examination of the seed germination rate, the plant length, and overall health of the plants compared to a control.

Figure 13 (a) highlights the experimental set-up on day 0, with (b) showing the end result of the control plants at day 10.

Observing Fig. 13b, the tomato plants exhibit cotyledon emergence after the specified time period, but are still within the germination phase and have not yet initiated full plant growth. An average plant size is 44.0 mm.

Figure 14 shows the end of the ten-day phytotoxicity test with the tomatoes using the liquid from the HTD process at one and five times the dosage. Both dosage amounts display increased growth rate, with the one-time dose increasing the average plant length by 5.45% to 46.4 mm, and the five times dose increases the average plant length by 90.0% to 83.6 mm. Neither sample, at these doses, exhibits signs of phytotoxicity in the tomato seeds; further testing will

be required to observe these limits. Both samples show improvement in tomato growth, allowing the tomatoes to complete the seed germination phase and transition into the plant growth phase, as indicated by the formation of leaves.

Conclusions

THC and CBD degradation was achieved at every HTD operating condition to a level at which no detectable content was observed. Therefore, processing cannabis waste using HTD conditions above 200 °C and 5 min meets the legislative conditions required to deconstruct this waste.

Throughout all the different times and temperatures of HTD, TSS and VSS decrease, while there is an increase in VFAs and ammonia formed. The complex molecules within the cannabis biomass are broken down and oxidised into smaller and simpler molecules, such as CO₂, acetic acid, and propanoic acid. VFAs, if able to be captured and separated, can add economic value to this reaction process. The conditions for the greatest concentration of total VFAs are at 5% feedstock, 300 °C, and 60 min.

The HTD product exhibits fertiliser properties that encourage plant growth, adding to the application available for the HTD product.

Limitations of this study include the characteristic testing of the solid component from the HTD process to identify other potential uses for this product stream.

Future work of this study would involve conducting process modelling from this data to determine the operating conditions necessary for taking this process further in a pilot study for production.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10098-026-03422-x>.

Acknowledgements The authors acknowledge Callaghan Innovation and Green Relief NZ Ltd for their financial support and funding. Acknowledgements also go to Alison Robertson, Corey Rozendaal, and Guy Lavender Forsyth for their continued support and editing of this study. Lastly, acknowledgements also go to Mr. Raymond Hoffmann, Dr. Matthew Sidford (Department of Chemical & Materials Engineering, the University of Auckland), Mrs. Hoa Nguyen (School of Environment, the University of Auckland), and Mr. Stuart Morrow (Faculty of Science, the University of Auckland) for technical assistance and helping with the chemical analyses.

Author contribution K.J.R. contributed to methodology, investigation, validation, and writing- original draft preparation; P.R. contributed to supervision and resources; S.B. contributed to conceptualisation, supervision, validation, writing- reviewing and editing.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. The Funding was provided by Callaghan Innovation.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The authors declare no competing interests.

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References

- Alba, C. (2021). Cannabis waste management in vancluver area.
- Bhatia SK, Yang Y-H (2017) Microbial production of volatile fatty acids: current status and future perspectives. *Rev Environ Sci Bio Technol* 16(2):327–345. <https://doi.org/10.1007/s11157-017-9431-4>
- Biller P, Ross AB (2016) 17-Production of biofuels via hydrothermal conversion. In: Luque R, Lin CSK, Wilson K, Clark J (eds) *Handbook of Biofuels Production* (Second Edition). Woodhead Publishing, Cambridge, pp 509–547
- Brunner G (2014) Chapter 10-Oxidation in High-Temperature and Supercritical Water. In: Brunner G (ed) *Supercritical fluid science and technology*. Elsevier, Amsterdam, pp 525–568
- Brunner G (2014) Chapter 13-Process components and processes. In: Brunner G (ed) *Supercritical fluid science and technology*, vol 5. Elsevier, Amsterdam, pp 621–647
- Chandra S, Lata H, ElSohly MA (2020) Propagation of cannabis for clinical research: an approach towards a modern herbal medicinal products development. *Front Plant Sci*. <https://doi.org/10.3389/fpls.2020.00958>
- Debellesfontaine H, Foussard JN (2000) Wet air oxidation for the treatment of industrial wastes. Chemical aspects, reactor design and industrial applications in Europe. *Waste Manag* 20(1):15–25. [https://doi.org/10.1016/S0956-053X\(99\)00306-2](https://doi.org/10.1016/S0956-053X(99)00306-2)
- García-Valverde MT, Sánchez-Carnerero Callado C, Díaz-Liñán MC, Sánchez de Medina V, Hidalgo-García J, Nadal X, Hanuš L, Ferreira-Vera C (2022) Effect of temperature in the degradation of cannabinoids: from a brief residence in the gas chromatography inlet port to a longer period in thermal treatments. *Front Chem*. <https://doi.org/10.3389/fchem.2022.1038729>
- Glass M (2019) What is medicinal cannabis? *The New Zealand Med J* 132(1494):1
- Jin D, Dai K, Xie Z, Chen J (2020) Secondary metabolites profiled in Cannabis inflorescences, leaves, stem barks, and roots for medicinal purposes. *Sci Rep* 10(1):3309. <https://doi.org/10.1038/s41598-020-60172-6>
- Kilgore UJ, Subramaniam S, Fox SP, Cronin DJ, Guo MF, Schmidt AJ, Ramasamy KK, Thorson MR (2023) Wet air oxidation of HTL aqueous waste. *Biomass Bioenergy* 176:106889. <https://doi.org/10.1016/j.biombioe.2023.106889>
- Marzorati S, Friscione D, Picchi E, Verotta L (2020) Cannabidiol from inflorescences of *Cannabis sativa* L.: green extraction and purification processes. *Ind Crops Prod* 155:112816. <https://doi.org/10.1016/j.indcrop.2020.112816>
- Mishra VS, Mahajani VV, Joshi JB (1995) Wet Air Oxidation. *Ind Eng Chem Res* 34(1):2–48. <https://doi.org/10.1021/ie00040a001>
- Munir MT, Mansouri SS, Udugama IA, Baroutian S, Gernaey KV, Young BR (2018) Resource recovery from organic solid waste using hydrothermal processing: opportunities and challenges. *Renew Sustain Energy Rev* 96:64–75. <https://doi.org/10.1016/j.rser.2018.07.039>
- Padoley KV, Tembhekar PD, Saratchandra T, Pandit AB, Pandey RA, Mudliar SN (2012) Wet air oxidation as a pretreatment option for selective biodegradability enhancement and biogas generation potential from complex effluent. *Bioresour Technol* 120:157–164. <https://doi.org/10.1016/j.biortech.2012.06.051>
- Prohibition Partners. (2021). The global cannabis report: second edition.
- Qin J, Aika K-i (1998) Catalytic wet air oxidation of ammonia over alumina supported metals. *Appl Catal B Environ* 16(3):261–268. [https://doi.org/10.1016/S0926-3373\(97\)00082-9](https://doi.org/10.1016/S0926-3373(97)00082-9)
- Robertson KJ, Brar R, Randhawa P, Stark C, Baroutian S (2023) Opportunities and challenges in waste management within the medicinal cannabis sector. *Ind Crops Prod* 197:116639. <https://doi.org/10.1016/j.indcrop.2023.116639>
- Silva Thomsen LB, Carregosa JdC, Wisniewski A, Anastasakis K, Biller P (2024) Continuous wet air oxidation of aqueous phase from hydrothermal liquefaction of sewage sludge. *J Environ Chem Eng* 12(3):112672. <https://doi.org/10.1016/j.jece.2024.112672>
- Strong PJ, McDonald B, Gapes DJ (2011) Combined thermochemical and fermentative destruction of municipal biosolids: a comparison between thermal hydrolysis and wet oxidative pre-treatment. *Bioresour Technol* 102(9):5520–5527. <https://doi.org/10.1016/j.biortech.2010.12.027>
- Tekin G, Ersöz G, Atalay S (2022) Valorization of biomass as co-catalyst for simultaneous remediation and hydrogen production from sugar industry wastewater by catalytic wet air oxidation. *J Clean Prod* 330:129728. <https://doi.org/10.1016/j.jclepro.2021.129728>
- Zewde AA, Li Z, Zhou X (2023) A review on the use and applications of volatile fatty acids on fecal sludge sanitization. *J Water Sanit Hyg Dev* 13(3):218–234. <https://doi.org/10.2166/washdev.2023.252>
- Zhang Y (2020) Wet oxidation technology based on organic wastewater treatment. *J Phys: Conf Series*. <https://doi.org/10.1088/1742-6596/1549/2/022040>
- Zhi Y, Wang Y, Xu D, Jiang G, Leng L, Kapusta K (2024) Phosphorus recovery from hydrothermal conversion products of sewage sludge through wet-chemical methods. *Process Saf Environ Prot* 182:1024–1034. <https://doi.org/10.1016/j.psep.2023.12.053>
- Zigová J, Šturdík E (2000) Advances in biotechnological production of butyric acid. *J Ind Microbiol Biotechnol* 24(3):153–160. <https://doi.org/10.1038/sj.jim.2900795>
- Zou LY, Li Y, Hung Y-T (2007) Wet air oxidation for waste treatment. In: Wang LK, Hung Y-T, Shammass NK (eds) *Advanced physicochemical treatment technologies*. Humana Press, New Jersey, pp 575–610

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