Phenolic-rich bio-oil production by microwave catalytic pyrolysis of switchgrass: Experimental study, life cycle assessment, and economic analysis

Badr A. Mohamed [1,2*], Muhammad Bilal [3], El-Sayed Salama [4], Selvakumar Periyasamy [5], I. M. Rizwanul Fattah [6], Roger Ruan [7] Mukesh Kumar Awasthi [8], and Lijian Leng [9*]

[1] Department of Agricultural Engineering, Cairo University, Giza, Egypt

[2] Department of Chemical Engineering, University of British Columbia, Vancouver, BC V6T 1Z3, Canada

[3] School of Life Science and Food Engineering, Huaiyin Institute of Technology, Huai'an, China

[4] Department of Occupational and Environmental Health, School of Public Health, Lanzhou University, Lanzhou City, Gansu Province 730000, China

[5] Department of Chemical Engineering, School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, Adama, 1888, Ethiopia

[6] Centre for Technology in Water and Wastewater (CTWW), Faculty of Engineering and IT, University of Technology Sydney, Ultimo, 2007 NSW Australia

[7] Center for Biorefining and Department of Bioproducts and Biosystems Engineering, University of Minnesota, 1390 Eckles Ave., St. Paul, MN 55108, USA

[8] College of Natural Resources and Environmental, Northwest A&F University, Taicheng Road 3#, Yangling, Shaanxi, 71200, China

[9] School of Energy Science and Engineering, Central South University, Changsha, Hunan 410083, China

[*]Corresponding authors:

Badr Mohamed; Email: Badrmoh@cu.edu.eg

Lijian Leng; Email: lljchs@126.com

Abstract

This study aims to determine the environmental impacts and feasibility of optimizing the production of phenolic-rich bio-oil, via switchgrass microwave catalytic pyrolysis. K_3PO_4 (Tripotassium phosphate) was used as the catalyst, at different temperatures, throughout this life cycle assessment (LCA) study. Results were compared with non-catalytic microwave pyrolysis (SiC-400) and conventional pyrolysis. K_3PO_4 (KP) was used as the microwave absorber and catalyst to enhance the low microwave absorption of switchgrass during microwave pyrolysis, and to improve the bio-oil quality and selectivity for phenolics production. Pyrolysis temperatures made a considerable difference to the LCA. There was an 86% reduction in the pyrolysis time when heating the sample to 300°C (KP-300), as compared to 400°C (KP-400), resulting in a significant reduction of the amount of energy required, and GHG's emitted. The total global warming potential (GWP) for microwave catalytic pyrolysis is observed within 159−223 kg CO_2-eq/1000 kg of dried switchgrass (SG), with the baseline case (SiC-400) being the highest, and KP-300 being the lowest. Using the produced biochar, which is rich in nutrients for soil application, brings the net GWP to negative values through carbon sequestration. KP-300 also showed the highest selectivity for phenol and alkylphenols production, which increased by 252% and 420% respectively, compared to the baseline. The results clearly indicate that introducing K_3PO_4 showed great potential for accelerating microwave heating, and improving bio-oil selectivity towards alkylphenols, which can be used to replace petroleum-based phenol. This in turn can reduce GHG emissions, due to higher conversion efficiencies and lower energy consumption compared with non-catalytic microwave pyrolysis and conventional pyrolysis.

Keywords: *Catalytic microwave pyrolysis optimization; Life cycle assessment; Phenolic-rich bio-oil; K_3PO_4; Carbon sequestration; Switchgrass*

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1. Introduction

Due to population explosion and up-grading the quality of life (Chan et al., 2020), fossil-based energy consumption has risen to alarming levels (Basafa and Hawboldt, 2021). The intensive usage of fossil fuel to meet the energy demand by both industrial and domestic sectors is boosting carbon emissions, which has remarkably increased the issues of global warming (Mohamed et al., 2022a). This extensive consumption is exhausting fossil fuel resources and has resulted in many environmental concerns. Therefore, the production and consumption of petroleum-based products such as phenols will be limited (Ma et al., 2020). Phenol and its derivatives are essential industrial chemical compounds, required for the production of multitudes of industrial products including resins (Bu et al., 2012). Therefore, valorizing renewable energy resources and phasing out petroleum-based resources for phenol production is a crucial need of our time (Chan et al., 2020).

Pyrolysis is a thermochemical degradation of material in an inert atmosphere that generates a variety of products such as non-condensable gases (NCG), biochar, and bio-oil, within a brief reaction time (Hu et al., 2021). Production of bio-oil from agricultural wastes (Chan et al., 2020) and wood wastes (Shu et al., 2019) is regarded as a cost-efficient and viable process. However, in a typical conventional pyrolytic process, bio-oil quality drops due to its poor selectivity (Wang et al., 2018) and complex chemical composition (Chan et al., 2020), making bio-oil unfavorable for fuel or chemical extraction applications (Lu et al., 2018). Bio-oil is characterized as a complex mixture, comprising almost all species of highly oxygenated organic compounds (Uzoejinwa et al., 2018) such as ketones, phenols, aromatic hydrocarbons, organic acids, aliphatic hydrocarbons, esters, ethers, aldehydes, and alcohols (Bu et al., 2012). The major challenge with bio-oil is high oxygen content, which affects its stability and lowers its energy density, in addition to being highly corrosive (pH= ~2.5) and viscous. These properties limit bio-oil usage in internal combustion engines (Lu et al., 2018),

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84 and therefore limit its potential application as a fuel replacement for fossil fuels (Chan et al.,

85 2020).

86   However, bio-oil can be upgraded to produce several bio-based chemicals that have a

87 variety of uses in many industries. For instance, biochemicals (e.g., phenolics and ketones)

88 are used as resins and solvents (Chan et al., 2020), while aromatic hydrocarbons are

89 employed as both fuels and solvents in industrial applications (Bu et al., 2012). Among bio-

90 oil fractions, phenols are the most commercially useful compounds. They can be used as raw

91 materials in many industries such as fine chemicals, pharmaceutical industry, resin

92 manufacturing, and food processing (Chan et al., 2020). Extensive research has been carried

93 out to assess the efficiency of hydro-deoxygenation (HDO) and catalytic fast pyrolysis for

94 transforming bio-oils into higher-grade biofuels. HDO is a widely used method to transform

95 low-value products into biofuels. However, the stability of benzene structure makes the

96 transformation of oxygenated phenolic compounds very difficult (Kim, 2015), and thus

97 research on phenolic compounds is an important consideration (Shu et al., 2019). Recently,

98 several studies have suggested that phenolic compounds can be isolated from bio-oils (Basafa

99 and Hawboldt, 2021), and this significantly facilitates the industrialization of the phenol

100 production from biomass (Kim, 2015).

101   Phenolic compounds can be generated by fast pyrolysis of lignin-based biomass, which

102 possess potential commercial value as they can be employed as a phenol substitute in

103 manufacturing phenolic resins (Basafa and Hawboldt, 2021). For obtaining aromatic and

104 phenolic compounds from bio-oil, catalytic pyrolysis was found as an effective process for

105 upgrading bio-oil selectivity and increasing its commercial value (Ma et al., 2020). It is

106 noteworthy that several studies in the literature focused on the production of phenolic

107 compounds at high pyrolysis temperatures (> 400 °C) (Wang et al., 2021).

108   To make pyrolysis more effective, microwave pyrolysis has been investigated as an

109 efficient method to enhance the quality of biochar, bio-oil, and syngas (Ma et al., 2020).

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110 Several studies have highlighted that the catalytic upgrading of liquid bio-oils (i.e., pyrolytic

111 vapors) can produce bio-oils rich in phenols (Lu et al., 2018). Further, mixing activated

112 carbon as a microwave absorber with biomass at high loads (> 40 wt%) can produce

113 phenolic-rich bio-oil under microwave pyrolysis (Wang et al., 2019). However, activated

114 carbon is very expensive (Mohamed et al., 2022b), which can cost > 10 US$/kg (Fingolo et

115 al., 2020), increasing bio-oil production cost remarkably, and limiting the potential industrial

116 application of the microwave pyrolysis process. No previous studies focused on microwave

117 pyrolysis of biomass at low pyrolytic temperatures (< 350°C) for producing phenol-rich bio-

118 oils and biochar rich in nutrients (Ma et al., 2021). Therefore, to achieve a higher yield of

119 phenolic products at a reduced cost (Periyasamy et al., 2022), it is imperative to select the

120 appropriate catalysts for enhancing bio-oil activity and optimizing phenolic production

121 (Wang et al., 2021). In order to promote a circular economy of biomass microwave catalytic

122 pyrolysis, the quality of the bio-oil and biochar should be simultaneously improved to

123 decrease production costs.

124 In our previous studies, it was found that mixing K_3PO_4 (Tripotassium phosphate) with

125 switchgrass enhanced the poor microwave absorption of switchgrass, boosted the microwave

126 heating rate (Mohamed et al., 2021a), and produced efficient biochar with high sorption

127 affinity for heavy metals (Mohamed et al., 2017) and increasing water holding capacity of

128 sandy soils (Mohamed et al., 2016a), and rich in nutrients (Mohamed et al., 2021b). To the

129 best of our knowledge, no previous studies have investigated the possibility of producing

130 phenolic-rich bio-oil at low temperatures or determined the feasibility and environmental

131 impacts of the process. To determine the sustainability and feasibility of the microwave

132 catalytic pyrolysis process for industrial application, life cycle assessment (LCA) and

133 economic analysis are highly need. Therefore, the objectives of this study are to (a)

134 investigate the effectiveness of K_3PO_4 as a catalyst for promoting the catalytic microwave

135 pyrolysis of biomass to produce phenolic-rich bio-oil at different pyrolysis temperatures; and

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136 (b) to quantify the environmental impacts and determine the feasibility of the production of

137 phenolic-rich bio-oil, and nutrient-rich biochar, through microwave catalytic pyrolysis of

138 switchgrass under different temperatures, in comparison with the conventional pyrolysis. For

139 the first time, this study provides a more detailed comparison to guide future research and

140 development on bio-oil and biochar production from microwave catalytic pyrolysis in a more

141 comprehensive manner. Pyrolysis temperature, liquid product yields, and bio-oil properties

142 are examined to determine their effects on phenolic production and selectivity, and to

143 quantify the environmental impacts of phenolic-rich bio-oil production under different

144 operating conditions.

145   To assess the potential of microwave catalytic pyrolysis for producing phenolic-rich bio-

146 oil, the environmental impacts such as human toxicity potential (HTP), acidification potential

147 (AP), global warming potential (GWP), eutrophication potential (EP), and photo-oxidant

148 formation potential (POCP) are determined based on switchgrass microwave catalytic

149 pyrolysis process though cradle-to-gate life-cycle assessment, and contrasted with those from

150 the non-catalytic microwave pyrolysis, and those from conventional pyrolysis in the

151 literature.

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2. Materials and methods

Switchgrass (SG) was used in this study for its bioenergy application potential. SG is a C4 plant that could be grown in a wide geographic areas to enhance the productivity of soil with less amounts of water and nutrients, and it was identified as a model energy crop by the US Department of Energy (Keshwani and Cheng, 2010). Most biomass materials have a low dielectric loss compared with that of good absorbers (e.g., activated carbon). Therefore, a microwave absorber is required to enhance microwave heating (Mohamed et al., 2022c). Thus, K_3PO_4 (Tripotassium phosphate) was incorporated with SG as a microwave absorber and catalyst to improve the poor microwave absorption of SG and hence expedite the heating rate of the catalytic pyrolysis process, thereby optimizing the characteristics of the biochar and gas and producing phenolic-rich bio-oil. Silicon carbide (SiC), an inert chemical and efficient microwave absorber, was incorporated with SG to enhance the weak microwave absorption by SG (Mohamed et al., 2016b). Pre-mixed SG catalyst samples were transferred into the reactor, and N_2 was supplied to create an anoxic environment at 1.5 L/min for nearly 30 minutes. The microwave was powered at 750 W and the sample's temperature was set to be 300 or 400°C (Mohamed et al., 2021b). To avoid the reflection of microwaves, collection of un-absorbed microwave was done by a water-cooling system. More information about experimental setup and procedures can be found in previous studies (Mohamed et al., 2021a).

2.1. Products characterization

To study the effects of K_3PO_4 on the bio-oil selectivity and deoxygenation performance, gas chromatography with mass spectrometer (GC/MS, Agilent 7820A GC and mass spectrometry detector Agilent 5975 Series MSD) was used to analyze the chemical composition of the whole bio-oil, including organic and aqueous components (Mohamed et al., 2021a). Helium (99.999% purity) was used as the carrier gas at a flow rate of 1 mL/min. C, H, N, and S contents of biochars were determined using a CHNS analyzer (PerkinElmer

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181 2400Series-II), and oxygen was determined by difference. More information on bio-oil and

182 biochar characterizations can be found in previous studies (Mohamed et al., 2021a).

2.2. Life cycle assessment of catalytic microwave pyrolysis

184 Life cycles assessment (LCA) was adopted in order to determine the environmental

185 impacts associated with catalytic microwave pyrolysis of SG. The environmental impacts

186 were measured using LCA data based on the experimental results, literature review, and data

187 from other energy-related organizations. In compliance with the methods defined in ISOs

188 14040 and 14044, the environmental impacts were determined. It is assumed that the process

189 is established in Canada.

2.2.1. Goal and scope

191 The purpose of this LCA analysis is to determine the environmental consequences and

192 the greenhouse gas (GHG) emissions of the production of phenolic-rich bio-oil and nutrient-

193 rich biochar produced through SG microwave catalytic pyrolysis under different temperatures

194 in comparison with the non-catalytic microwave pyrolysis and conventional pyrolysis.

195 Contribution analysis was conducted to identify the processes contributing drastically to

196 energy consumption, GWP, and other environmental impacts. The standardized methodology

197 of life LCA was followed using Open LCA with Ecoinvent version 3.71 Unit Process

198 database (Alengebawy et al., 2022). The method for the life cycle impact assessment (LCIA)

199 for this study is ReCiPe 2016 Midpoint (H). 1000 kg of dried switchgrass material (DM) was

200 used as a functional unit. The system boundary includes the following processes: 1) Transport

201 of switchgrass, 2) Drying, 3) Grinding and Screening, 5) Storage, 6) Feeding, 7) Pyrolysis, 8)

202 Cooling, and 9) Transport of products (bio-oil and biochar) (Figure 1).

2.2.2. Life cycle inventory

204 The LCA is performed based on SG pyrolysis process cradle-to-gate and contrasted with

205 the non-catalytic microwave pyrolysis and conventional pyrolysis from literature. The non-

206 condensable gases (NCG) can be used for energy recovery using the combined heat and

207 power (CHP) system; however, their environmental impacts are not taken into consideration

208 because the combustion data are not available. To investigate the acidification,

209 eutrophication, and human toxicity potential as well as to calculate the specific GHG

210 emissions of microwave catalytic pyrolysis of SG, the life cycle inventory (LCI) was

211 compiled from primary data collected from the experimental work and different literatures

212 (Mong et al., 2021). The electricity consumed for the drying stage was determined assuming

213 initial moisture of 25 wt% for SG, which is thermally dried to 8 wt% before being grinded,

214 screened, and fed into the reactor (Huang et al., 2022). Pyrolysis is conducted at 300 or 400

215 °C, and vapors are condensed to produce bio-oil, biochar and NCG. For transportation, it is

216 assumed that SG is transported from 50 km distance, and bio-oil and biochar are sold to local

217 customers within 25 km distance from the production site using a 16-tonne truck.

2.2.3. Biochar and carbon sequestration

219 The carbon sequestered in the biochars was determined based on the elemental

220 composition of the biochars (Leng et al., 2021). The stability of the biochar and available

221 environmental credit could be predicted depending on the H/C and O/C ratios in the char

222 products (Enders et al., 2012). It has been shown that the relationship between oxygen and

223 carbon in the biochar and carbonaceous materials structure governs stability: carbonaceous

224 materials with an O/C molar ratio of less than 0.2 (e.g. graphite, some biochars) are typically

225 the most stable, possessing an estimated half-life of more than 1000 years; biochar with an

226 O/C ratio of 0.2–0.6 (most biochars) have intermediate half-lives (100–1000 years); and,

227 finally biochar with an O/C ratio of greater than 0.6 (biomass) possess a half-life within 100

228 years (Méndez et al., 2012). The O/C molar ratio for KP-300 and KP-400 biochars are 0.32

229 and 0.37, respectively as shown in Table 1, demonstrating that the carbon in biochars would

230 last for more than 100 years.

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2.2.4. Impact assessment and sensitivity analysis

For determining the impacts of microwave pyrolysis systems on global warming, the main GHGs carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were considered, using CO_2 equivalence factors (mass basis) for a 100-year time horizon with a global warming potential (GWP) of 298 for N_2O and 25 for CH_4. The avoided GHGs emissions through carbon sequestration of biochar in soil, the replacement of GHG emissions related to fuel oil combustion #2 (2570 g CO_2-eq/L) are included in the estimated GHG emissions (Brassard et al., 2018). The NCG from microwave pyrolysis can be recovered to provide energy for drying the wet switchgrass, which can be used to replace hydroelectricity. For biochar-400, it is assumed that 85% of the C in biochar remains in soil for 100 years (BC+100 of 85%), and 90% of the C in biochar remains in soil for 100 years for biochar KP-300 (BC+100 of 90%) based on their O/C and H/C molar ratios (Brassard et al., 2018).

To determine the energy balance for pyrolyzing 1000 kg of dried SG, the energy inputs including energy consumption for drying, grinding and screening, feeding, pyrolysis, and quenching, in addition to energy output from NCG and bio-oil were also included. NCG can be used to substitute hydroelectricity to produce heat. The conversion efficiency from NCG to heat is estimated to 75% (Brassard et al., 2018), which can be used to substitute hydroelectricity (Huang et al., 2022).

2.2.5. Economic analysis

A preliminary assessment of the annual production cost and profit from selling the pyrolysis products was performed for all scenarios to see if the processes are economically viable throughout the operating period. The costs of raw materials and the pyrolysis products are presented in Table S1 in the supplementary material. Since the cost of raw materials, electricity pricing, the selling prices for pyrolysis products vary widely, three cases were considered for the economic assessment, including low-case, base-case, and high-case values, which are summarized in Table S1. Based on the provided economic analysis results, the

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259 proportion of the operational cost for all scenarios is set at 36% of the utility cost (Barry et

260 al., 2019). The total production cost (TPC) was calculated based on the costs of utility, raw

261 materials, including chemicals, and operational cost. The net profits of the scenarios are then

262 determined based on income from product sales after deducting TPC.

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3. Results and discussion

3.1. Effect of K_3PO_4 on heating behaviour and pyrolysis products

266 It was found that SG absorbs microwaves ineffectively, and the maximum temperature

267 recorded was < 150°C (Mohamed et al., 2016b). Thus, no bio-oil or biochar was produced

268 from SG without a catalyst. However, mixing K_3PO_4 with SG enhanced the microwave

269 heating, significantly, reaching 300 and 400°C in 2.10 and 15.30 min, respectively. The KP-

270 400 sample took a longer time to reach 400°C, because of the oxygenated coke deposition on

271 the catalyst surfaces, as a result of hemicellulose inhibition (Mohamed et al., 2019a).

272 Oxygenated coke deposition on catalyst surfaces was found to reduce microwave absorption,

273 remarkably (Mohamed et al., 2019b). For the effect of temperature on the distribution of

274 pyrolysis products, K_3PO_4 increased biochar and reduced bio-oil yields at higher temperature

275 because of the coke deposition (Table 1). In contrast, there are several microwave absorbing

276 materials that have been used for enhancing the microwave absorption of biomass materials,

277 including carbonaceous materials such as activated carbon, graphene (Dong et al., 2019),

278 graphite (Zhang et al., 2020), and carbon nanotubes (Wei et al., 2020). However, most of

279 these materials are relatively expensive (Wang and Wang, 2019) and do not have high

280 catalytic activity for producing high-quality phenolic-rich bio-oil. Whereas, K_3PO_4 can

281 enhance the microwave heating, produce phenolic-rich bio-oil, and remain in the produced

282 biochars to serve as source of nutrients for plants.

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3.2. Effect of K_3PO_4 on bio-oil selectivity and phenol production

When compared with the baseline sample (SiC-400), K_3PO_4 demonstrated a greater deoxygenation potential, with remarkable reduction of the highly reactive oxygenated compounds, including acetic acid, and furans, and the complete removal of the other oxygenates including aldehydes and anhydro-sugars (Table 2). The detailed compositions of bio-oil for different KP samples compared with the baseline, are presented in Table 3. The acidic compounds responsible for bio-oil acidity were reduced by ~75% under both pyrolysis temperatures, compared with the baseline. Furan compounds were significantly reduced by 85% and 79%, in comparison with the baseline, for KP-300 and KP-400, respectively. However, K_3PO_4 improved bio-oil selectivity towards phenolic production, and the phenolic and aromatic compounds were dramatically increased by 385% and 303% for KP-300 and KP-400. This eventually enhanced the energy density and stability of the bio-oil. These findings agree with previous studies (Lu et al., 2018), in which K_3PO_4 measurably increased phenolics content in bio-oil (Lu et al., 2013). Commercial activated carbon has been found to improve bio-oil selectivity towards phenolic production (Ma et al., 2020). Similarly, HZSM-5 was also found to increase phenolics content through the conversion of furan compounds into aromatics, and then converting aromatics into phenolics on catalytic surfaces (Wang et al., 2019). HZSM-5 was also found promote alkylation reactions, which increased the production of alkylated phenols (Yathavan and Agblevor, 2013). It was also reported that combining bentonite and HZSM-5 improved bio-oil selectivity by creating more aromatics than HZSM-5 without bentonite (He et al., 2018). However commercial activated carbon and HZSM-5 are very expensive (Müller et al., 2015), and coke coverage could decrease catalytic conversion efficiency and deactivate the catalysts irreversibly (Wang et al., 2014). Ma and coworkers studied the effects of using Ni/SiO_2, Ca/SiO_2, and $Ni–Ca/SiO_2$ for producing phenolic-rich bio-oil from waste chilli stem biomass, and $Ni–Ca/SiO_2$ showed high catalytic activity for increasing phenolics by 150% compared with the sample without a catalyst (Ma et al., 2021).

311 MgO and biomass-derived activated carbon catalysts were used to produce phenolic-rich bio-

312 oil from Douglas fir and it was found that oxygenated phenols dominated, accounting for up

313 to 80% of the phenols (Huo et al., 2020).

314 In contrast, a significant increase was observed in the generation of phenolics, and many

315 other aromatics compounds, due to the catalysts used, where KP-300 indicated the highest

316 production in phenolics. Subsequently, a complete elimination of hemicellulose derived

317 compounds, including linear aldehydes, occurred during the pyrolysis reactions. Through

318 catalytic pyrolysis, oxygenated substances such as acetic acid, furfuryl alcohol, furans, and

319 furfurals are easily transformed to aromatics (Carlson et al., 2010). The results of the kinetic

320 analysis revealed that K_3PO_4 greatly catalyzed tar cracking, and promoted lignin

321 decomposition (Mohamed et al., 2020), which helps to explain the remarkable increase in

322 phenolics content, compared with the baseline data.

323 The effects of catalytic microwave pyrolysis, using K_3PO_4 on phenolic and aromatic

324 species under different pyrolysis temperatures, are shown in Figure 2. It is found that K_3PO_4

325 enhanced bio-oil selectivity for the production of phenolic compounds including phenol and

326 alkylphenols, and KP-300 showed the highest selectivity for the production of phenol and

327 alkylphenols, which increased by 252% and 420% in comparison with the baseline, whereas

328 phenol and alkylphenols increased by only 9% and 18% compared to KP-400. Although

329 phenolic-rich bio-oils lack reactivity for synthesizing phenolic resins, they possess a high

330 content of phenolic compounds and offer an effective replacement of phenol produced from

331 fossil fuel. Most bio-oils reported in previous studies, were composed of a small amount of

332 reactive phenol and a mix of phenolics that include aromatic ethers and alkylated phenol.

333 This complex nature makes it less attractive when compared to pure phenol (Kim, 2015).

334 However, the addition of phenolic-rich bio-oil for the production of formaldehyde phenolic-

335 resin, demonstrated a good capability for substituting fossil fuel phenols (Kim, 2015). It was

336 found that phenol synthesis is significantly impacted by the pyrolytic conditions, such as

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337 catalyst type, temperature, and catalyst content (Lu et al., 2018). Phenol production and

338 phenol yield were observed to be higher from pinewood rather than poplar wood. In order to

339 lower the extra hydrogen supplied, mixed pyrolysis gas was utilized to maintain a uniform

340 provision of hydrogen atmosphere for phenol production (Lu et al., 2018).

341   Vanillin is one of the most unstable and reactive oxygenated phenolic compounds (Chen

342 et al., 2020), which has a poor stability in comparison to other phenolics (Oh et al., 2017).

343 Consequently, the removal of such reactive compounds can progressively increase the

344 chemical stability of the bio-oil. Due to their similar properties with phenol, alkylphenols are

345 regarded as commercially beneficial chemicals. For instance, it is widely applied in the

346 production of polymer building blocks. Alkylphenols can be employed as a cost-effective

347 solvent for isolating oxygenated compounds from aqueous solutions, derived by biomass that

348 include furfural compounds, levulinic acid, and gamma-valerolactone. Hence, alkylphenols

349 have a great ability to be used as a chemicals platform, it is thus important to create a viable

350 approach to produce bio-oils rich in alkylphenols (Shu et al., 2019). Octane number and

351 heating value are higher in alkylated phenols than oxygenated phenols, which makes them

352 preferable compounds to be extracted from bio-oils (Zabeti et al., 2012). For instance, methyl

353 phenol and phenol have similar heating values of 34.15 and 33.11 MJ/kg, respectively (Zabeti

354 et al., 2012). Aromatic hydrocarbons, specifically those compounds having a higher octane

355 number, are useful chemicals that can be employed as octane enhancers in gasoline (Rezaei et

356 al., 2014).

3.3. Life cycle assessment

358   The total estimated energy consumption for bio-oil production including drying, grinding

359 and screening, feeding, pyrolysis, etc. are 727, 1,125, and 1,260 KWh/1000 kg dried SG for

360 KP-300, KP-400, and SiC-400, respectively (Table 1). The drying stage for the raw material

361 contributed by 22% and 14%, while the microwave pyrolysis process contributed by 76% and

362 85% for KP-300 and KP-400, respectively, confirming that initial drying of the feedstock

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363 material requires a significant amount of energy. These findings are in line with the other

364 studies in the literature, revealing that other drying methods such as solar drying could be

365 utilized to further reduce the energy consumption of the process. The percentage of the

366 environmental impacts for each process involved in the production of bio-oil including

367 transporting the raw material and final products (bio-oil and biochar) is shown in Figure 3.

368   Drying and pyrolysis stages contributed remarkably to GWP for all cases, while the

369 transportation of SG and pyrolysis products (bio-oil and biochar) is the major contributor to

370 all other environmental indicators, except the GWP (Figure 3). This is in agreement with

371 other reported studies in literature, in which transportation has been found to have a major

372 influence on the eutrophication potential (EP) (Peters et al., 2015) and acidification potential

373 (AP) (Roberts et al., 2010). The breakdown values of the environmental impacts for each

374 process are presented in Table 4. For EP, the values ranged from 0.024 to 0.041 kg PO_4^{3-}

375 eq/1000 kg DM, while AP values ranges are 0.136−0.151 kg SO_2 eq/1000 kg DM. These EP

376 values are remarkably low when compared with conventional pyrolysis, in which

377 conventional pyrolysis could contribute to EP by 1.39 kg PO_4^{3-} eq/1000 kg DM and for AP

378 by 0.045 kg SO_2 eq/1000 kg DM, respectively (Wang et al., 2015). The remarkable effects of

379 drying and microwave pyrolysis on GWP (Table 4 and Figure 3) are due to their significant

380 energy consumption. However, microwave catalytic pyrolysis has less impact on GWP

381 (159−223 kg CO_2-eq/1000 kg DM) when compared to conventional pyrolysis, in which the

382 GWP from conventional pyrolysis ranged from 737 CO_2-eq/1000 kg DM (Wang et al., 2015)

383 to 1,295 kg CO_2-eq/1000 kg DM (Muñoz et al., 2017). Other studies found that reducing

384 pyrolysis temperatures from 400 to 300°C resulted in a remarkable reduction in the negative

385 environmental impacts, including human toxicity, and freshwater eutrophication, which

386 reduced the impacts by 38% and 56%, respectively (Muñoz et al., 2017).

387   Acidification potential, which has a substantial influence on the environment, is linked

388 with emissions of compounds, such as SO_2, NOx, NH_3, and hydrocarbons. Those acidic

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389 chemicals (excluding NH_3) could react to create acid rain with other atmospheric

390 components. Acid rain may decrease the pH of soil and water (Johansson et al., 2008) and

391 damage environments for many living organisms (Vienescu et al., 2018). The EP is described

392 as the rise in organic matter input in the environment. The PO_4^{3-} equivalents are assessed

393 based on NH_3 and NOx levels (PO_4^{3-} eq). The EP examines all the consequences on the air,

394 water, and soil environments released by high macronutrients levels (Vienescu et al., 2018).

395 Microwave heating has been claimed to decrease energy use by more than 50% in

396 comparison with conventional heating systems (Mohamed et al., 2016b). However, this

397 mainly depends on microwave absorption ability of a feedstock, and a good microwave

398 absorber should be mixed with the feedstocks having poor absorption ability for microwaves.

399 In microwave pyrolysis, the sample is heated immediately, as microwaves directly transmit

400 electromagnetic energy, leading to immediate and volumetric heating (Kostas et al., 2017).

401 As a result, microwave pyrolysis of large particles is possible without the requirement for an

402 energy-intensive grinding to produce smaller particle sizes (Zhou et al., 2013). It was claimed

403 that the energy required for pre-treatment processes accounted for up to 55% of the energy

404 required for the complete conventional pyrolysis process. This considerable quantity of

405 energy might be conserved in part by employing a microwave pyrolysis technique, resulting

406 in a large cost reduction (Beneroso et al., 2017).

407 Figure 4 compares CO_2 generated from microwave catalytic pyrolysis of SG with avoided

408 CO_2 credits from utilizing pyrolysis products through carbon sequestration and fuel

409 replacement, and the net value of GWP under different pyrolysis temperatures was also

410 compared. It is shown that most of the avoided CO_2 credits were achieved through replacing

411 bio-oil with the diesel fuel for the KP-400 sample, while the credit obtained from NCG is the

412 lowest (~8.9 kg CO_2-eq/kg 1000 kg DM) assuming that NCG is used on-site to replace

413 hydroelectricity. However, the emission from NCG combustion are not considered according

414 to previous studies (Muñoz et al., 2017), and thus future studies should focus on determining

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the actual emissions from NCG combustion. If NCG is used to replace natural gas, then the

value remarkably increases, leading to a remarkable increase in the net avoided GWP. It was

found that the avoided CO_2 credit of NCG for replacing electricity produced by natural gas

combined-cycle power generation system is 527 kg CO_2-eq/kg 1000 kg DM (Mong et al.,

2021). The biochar produced at low pyrolysis temperature (KP-300) contributed more to

avoided carbon with the highest net negative GWP of -665 CO_2-eq per 1000 kg dried SG

(Figure 5). This is because of its higher carbon content and high aromaticity, which is

confirmed by the low O/C ratio. Also, the biochars from KP-300 and KP-400 contain high

amounts of essential nutrients including K (304−385 g/kg), P (168−195 g/kg), Ca (14.2−23.3

g/kg), and other nutrients (Mohamed et al., 2021b), which make the biochars more desirable

for soil application.

Generally, the results show that the total net avoided GWP for KP-300 is higher than that

of KP-400; this result is due to the reduction in microwave energy consumption and increased

credit for biochar carbon sequestration. The LCA analysis reveals that microwave catalytic

pyrolysis is a potential novel approach for SG utilization that may help reduce the GWP

through sustainable utilization of agricultural wastes.

3.4. Sensitivity analysis

The sensitivity analysis for GWP is conducted on the basis of environmental analysis to

examine the effects of the main factors on sustainability of the process. The analysis includes

SG initial moisture content and microwave pyrolysis, as illustrated in Figure 5. The total

GWP is observed to range from 159 to 223 CO_2-eq per 1000 kg dried SG, as shown in Table

4. The moisture content of the collected SG imposed a great impact on the overall GWP

(Figure 3). The overall GWP would be lowered by 11−14% if SG is dried by sun to a

moisture level of 15 wt%. Further, reducing the consumed electricity through microwave

pyrolysis by 25% decreases the GWP by 15% when compared with the original case. This

can be achieved by mixing another good microwave absorber with K_3PO_4 to trigger

441 synergistic effects for expediting microwave heating. Our previous studies showed that

442 mixing two catalysts with biomass can trigger synergetic effects (Mohamed et al., 2020),

443 which resulted in expediting microwave heating and improving bio-oil quality and selectivity

444 (Mohamed et al., 2021a). The produced bio-oils are rich in phenolics that can be used for

445 substituting fossil fuel phenols. The bio-oil can be used for diesel fuel replacement; however,

446 upgrading is essential to further increase its calorific value and reduce the oxygen content of

447 the bio-oil. Bio-oil upgrading can further enhance energy recovery, which largely depends on

448 the calorific value and bio-oil oxygen content. Nevertheless, bio-oil upgrading is an energy-

449 intensive process (Peters et al., 2015) and therefore, requires more energy inputs than the

450 recovered energy from the upgraded bio-oil (Zhang, 2014). Bio-oil from this study can then

451 be used for phenols extraction due to its high phenolic content. Further investigation is

452 needed to evaluate whether it is a reasonable decision to implement bio-oil upgrading.

3.5. Economic analysis

454 The economic analysis results of the microwave pyrolysis scenarios with different

455 estimates (i.e., low-case, high-case, and base-case) are summarized in Table 5. When

456 considering the low-case estimates for selling pyrolysis products, only KP-300 was found to

457 provide a low marginal net profit. However, for other pyrolysis scenarios, no revenues were

458 generated from pyrolysis products, resulting in a negative profit. Previous studies found that

459 slow and fast pyrolysis processes are not profitable when considering high electricity price

460 (Kung et al., 2013). However, in this study, the cost of the chemicals contributes remarkably

461 to the TPC, therefore, lowering the mixing ratio of the chemicals can result in a positive

462 profit. Whereas, all pyrolysis scenarios generated revenues from pyrolysis products, resulting

463 in a positive profit after considering the base-case and high selling prices for pyrolysis

464 products (Table 5). For all cases, the gas products earned the lowest amount of money

465 (Shahbeig and Nosrati, 2020), in which the revenue was determined based on electricity

466 credit. According to other studies in literature, the bio-oil produced did not yield considerable

18

467 income, owing to their low quality (Iribarren et al., 2012; Kung et al., 2013). The bio-oil and

468 biochar yields, and their market values are significant factors in the process net profit. In

469 order to make the process more profitable, the marketable values should be at least within the

470 base-case estimated prices.

471 Considering the three ranges of the estimates, the TPC cost ranges from 526−1,220

472 US$/1000 kg dried SG with KP-300 being the lowest and SiC-400 being the highest. The cost

473 of chemicals (i.e., K_3PO_4, SiC) is the major contributor to TPC, which ranges from

474 37%−55%. The microwave pyrolysis costs are also similar to numbers proposed by previous

475 studies, which estimated the production cost to be ~640 US$/1000 kg for fast pyrolysis

476 (Brown et al., 2011).

477 The main limitation of this study is that other environmental effects resulting from using

478 biochar on land application, such as the release of GHG emissions, were not considered. The

479 limited boundary in this study also should be considered, and future studies should compare

480 different routes for extracting phenols from bio-oil and compare the feasibility and

481 profitability of different processes. Future studies should also focus on the environmental

482 impacts of extracting phenolic compounds from bio-oil, and determine the feasibility of the

483 process, compared with phenols derived from fossil fuel sources.

484

4. Conclusions

486 This study employed the life cycle analysis method to analyze the climate change and

487 energy effect from microwave catalytic pyrolysis of switchgrass at different pyrolysis

488 temperatures, for producing phenolic-rich bio-oil. The results show that microwave catalytic

489 pyrolysis, using K_3PO_4 can produce a phenolic rich bio-oil at lower temperatures compared

490 with conventional pyrolysis. KP-300, which was pyrolyzed at 300°C, showed the highest

491 selectivity for phenol and alkylphenols production, which increased by 252% and 420% in

492 comparison with the baseline (SG with SiC but without K_3PO_4). The total GWP is observed

493 to range from 159 to 223 kg CO_2-eq per 1000 kg dried SG, with KP-300 being the lowest.

494 Sensitivity analysis shows that drying and microwave pyrolysis are the most important

495 parameters that can be optimized during microwave catalytic pyrolysis to further reduce the

496 negative environmental burdens. The produced biochar is rich in nutrients, which can be used

497 for soil applications, leading to further reduction in the GWP through carbon sequestration.

498 The highest negative GWP of -398 kg CO_2-eq per 1000 kg dried SG was found for KP-300.

499 The economic analysis shows that microwave catalytic pyrolysis is an eco-friendly and

500 profitable process for recycling biomass feedstocks. This study demonstrates that the catalytic

501 microwave pyrolysis of switchgrass has lower environmental effects than non-catalytic

502 microwave pyrolysis and conventional pyrolysis because of the greater conversion efficiency

503 and lower energy consumption, lowering the carbon footprint while simultaneously

504 improving the quality of bio-oil and biochar.

505

510

511 **Conflict of interest**

512 The authors declare that the research was conducted without any influence of financial or

513 personal relationships that can potentially be the source of conflict of interest.

514

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733 **Table 1.** LCA inventory data for SG microwave catalytic pyrolysis.

Item	SiC-400	KP-300	KP-400	Notes
Biochar yield (wt%)	28.59	42.80	44.23	
Bio-oil yield (wt%)	30.38	32.15	28.98	Experimental data
NCG yield (wt%)	41.03	25.05	26.80	
Biochar elemental composition				
C (wt%)	51.48	28.22	25.86	
H (wt%)	2.86	1.93	1.40	
N (wt%)	0.94	0.64	0.31	Measured
O (wt%)	23.1	12.03	12.76	
O/C (%)	0.34	0.32	0.37	
H/C (%)	0.66	0.82	0.65	
Biochar carbon sequestration	395 kg CO_2/1000 kg DM	398 kg CO_2/1000 kg DM	356 kg CO_2/1000 kg DM	Calculated using data from (Brassard et al., 2018).
Transportation of SG and catalyst	257.8 MJ/1000 kg DM			Calculated
Pre-treatment stage				
Electricity for drying	579.8 MJ/1000 kg DM			Calculated
Electricity for SG grinding and screening	38.65 MJ/1000 kg DM			Calculated
Pyrolysis stage				
Electricity for SG feeding to the reactor	1.11 MJ/1000 kg DM			Calculated
Electricity for microwave pyrolysis of SG	3,915 MJ/1000 kg DM	1,997 MJ/1000 kg DM	3,432 MJ/1000 kg DM	Calculated
Cooling for pyrolysis vapors	1.08 MJ/1000 kg DM	1.012 MJ/1000 kg DM	1.05 MJ/1000 kg DM	Calculated
Total energy consumption	4,536 MJ (1,260 KWh)/1000 kg DM	2,616 MJ (727 KWh)/1000 kg DM	4,050 MJ (1,125 KWh)/1000 kg DM	Calculated
Transportation of products				
Bio-oil	32.73 MJ/1000 kg DM	34.54 MJ/1000 kg DM	31.12 MJ/1000 kg DM	Calculated
Biochar	30.48 MJ/1000 kg DM	45.99 MJ/1000 kg DM	47.53 MJ/1000 kg DM	

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735 NCG: non-condensable gases, SG: switchgrass
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Table 2. The concentrations of lumped main products of bio-oil from microwave pyrolysis of SG for KP-300 and KP-400 cases compared with SG mixed with SiC (baseline).

Samples	Linear Acids	Linear Aldehydes	Linear Ketones	Linear Alcohols	Furans	Anhydrosugars	Phenolics and Aromatics
SG + SiC-400	24.26	1.23	16.50	0.28	5.44	0.63	11.01
SG + KP-300	6.54	0.00	13.37	0.00	0.84	0.00	50.46
SG + KP-400k	5.95	0.00	6.48	0.94	1.15	0.00	44.39

KP: K_3PO_4, SG: switchgrass, SiC: silicon carbide

Table 3. Chemical composition of bio-oil (peak area %) produced from KP-300 and KP-400
cases compared with SG mixed with SiC (baseline).

	Compounds	Formula	SG + SiC-400	SG + 30KP-300	SG + 30KP-400
1	Acetic acid	$C_2H_4O_2$	21.95	5.39	4.87
2	Propanoic acid	$C_4H_8O_2$	2.31	1.15	1.08
3	Propanal, 2-methyl-	C_4H_8O	1.23	-	-
4	2-Propanone, 1-hydroxy-	$C_3H_6O_2$	10.14	4.77	0.50
5	2-Cyclopenten-1-one	C_5H_6O	1.75	1.30	0.64
6	1-Hydroxy-2-butanone	$C_4H_8O_2$	3.00	1.75	0.89
7	2-Propanone, 1-(acetyloxy)-	C_5H_8O3	-	-	0.46
8	2-Butanone, 3-hydroxy-	$C_4H_8O_2$	-	-	-
9	2-Cyclopenten-1-one, 3-methyl-	C_6H_8O	0.47	0.86	1.15
10	2-Cyclopenten-1-one, 2-methyl-	C_6H_8O	-	1.07	-
11	2-Cyclopenten-1-one, 2,3-dimethyl-	$C_7H_{10}O$	-	1.17	0.78
12	3,5-Dimethyl cyclopentenolone	$C_7H_{10}O_2$	-	0.99	1.11
13	2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	$C_7H_{10}O_2$	-	-	-
14	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	$C_6H_8O_2$	1.14	1.46	0.94
15	Furfural	$C_5H_4O_2$	3.09	-	-
16	2-Furancarboxaldehyde, 5-methyl-	$C_6H_6O_2$	0.52	-	-
17	2-Furancarboxaldehyde, 5-(hydroxymethyl)-	$C_6H_6O_3$	0.64	-	-
18	2(3H)-Furanone, dihydro-	$C_4H_6O_3$	0.52	0.84	0.51
19	2-Furanmethanol	C_5H6O_2	0.68	-	0.64
20	1,2-Ethanediol	$C_2H_6O_2$	0.28	-	0.94
21	Phenol	C_6H_6O	1.65	7.59	6.95
22	Phenol, 2-methoxy-	$C_{10}H_{12}O_2$	1.54	5.44	3.35
23	Phenol, 2-methoxy-4-methyl-	$C_8H_{10}O_2$	0.58	1.30	1.23
24	Phenol, 2,6-dimethoxy-	$C_8H_{10}O_3$	0.96	3.07	2.14
25	Benzeneethanol, 2-methoxy-	$C_9H_{12}O_2$	-	-	-
26	Phenol, 4-ethyl-2-methoxy-	$C_9H_{12}O_2$	0.40	-	-
27	Phenol, 2-methoxy-4-(1-propenyl)-	$C_{10}H_{12}O_2$	-	1.96	0.75
28	Benzeneethanol, 2-methoxy-	$C_9H_{12}O_2$	-	1.89	1.59
29	Benzene, 1-ethyl-4-methoxy-	$C_9H_{12}O$	-	-	-
30	Benzenemethanol	C_7H_8O	-	2.49	2.67
31	1,4-Benzenediol	$C_6H_6O_2$	-	-	-
32	Vanillin	$C_8H_8O_3$	1.12	-	-
33	Isovanillin	$C_8H_8O_3$	-	-	-
34	Phenol, 2,4-dimethyl-	$C_8H_{10}O$	-	-	2.49
35	Phenol, 2,3-dimethyl-	$C_8H_{10}O$	-	2.47	-
36	Phenol, 2,6-dimethyl-	$C_8H_{10}O$	-	-	-
37	Phenol, 3,4-dimethyl-	$C_8H_{10}O$	-	-	-
38	Phenol, 3,5-dimethyl-	$C_8H_{10}O$	-	0.88	-
39	Phenol, 4-methyl-	C_7H_8O	0.50	-	3.04
40	Phenol, 3-methyl-	C_7H_8O	0.41	3.33	-
41	Phenol, 4-(1-methylethyl)-, acetate	$C_{11}H14O_2$	-	-	0.63

42	Phenol, 4-ethyl-	$C_8H_{10}O$	0.72	3.07	4.97
43	Phenol, 3-ethyl-	$C_8H_{10}O$	-	-	0.71
44	Phenol, 2-ethyl-	$C_8H_{10}O$	-	-	0.89
45	Phenol, 3-ethyl-5-methyl-	$C_9H_{12}O$	-	-	0.55
46	Phenol, 4-ethyl-3-methyl-	$C_9H_{12}O$	-	-	-
47	2-Methoxy-4-vinylphenol	$C_9H_{10}O_2$	1.29	4.57	1.29
48	Phenol, 2-methyl-	C_7H_8O	0.45	2.70	2.65
49	1,1'-Bipheny	$C_{12}H_{10}$	-	-	-
50	4 - methyl - syringol	$C_9H_{12}O_3$	-	1.03	0.58
51	4-vinylphenol	C_8H_8O	1.39	6.68	3.26
52	Naphthalene	$C_{10}H_8$	-	-	-
53	Naphthalene, 1-methyl-	$C_{11}H_{10}$	-	-	-
54	Naphthalene, 2-methyl-	$C_{11}H_{10}$	-	0.99	0.94
55	Indene	C_9H_8	-	-	-
56	Azulene	$C_{10}H_8$	-	-	1.40
57	Anthracene	$C_{14}H_{10}$	-	-	-
58	9H-Fluorene	$C_{13}H_{10}$	-	-	0.47
59	2,3,5-Trimethoxytoluene	$C_{10}H_{14}O_3$	-	-	0.99
60	Biphenylene	$C_{12}H_8$	-	0.98	0.87
61	Acenaphthylene	$C_{12}H_8$	-	-	-
62	Phenanthrene	$C_{14}H_{10}$	-	-	-
63	1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	$C_6H_8O_4$	0.63	-	-
64	2,3-Anhydro-d-mannosan	$C_6H_8O_4$	0.00	-	-

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Table 4. Environmental impacts of different stages involved in the microwave catalytic pyrolysis of 1000 kg of dried SG for KP-300 and KP-400 cases compared with the baseline (SiC-400) and conventional pyrolysis from literature.

	GWP (kg CO$_2$ eq)			EP (kg PO$_4^{3-}$ eq)			AP (kg SO$_2$ eq)			HTP (kg DCB eq)			POCP (kg C$_2$H$_4$ eq)		
	SiC-400	KP-300	KP-400	SiC-400	KP-300	KP-400	SiC-400	KP-300	KP-400	SiC-400	KP-300	KP-400	SiC-400	KP-300	KP-400
Drying	5.73E+01	5.73E+01	5.73E+01	1.28E-02	3.03E-03	3.03E-03	1.28E-02	1.28E-02	1.28E-02	2.56E-02	2.56E-02	2.56E-02	7.61E-04	7.61E-04	7.61E-04
Grinding + Screening	9.91E+00	9.91E+00	9.91E+00	2.21E-03	5.22E-04	5.22E-04	2.21E-03	2.21E-03	2.21E-03	4.43E-03	4.43E-03	4.43E-03	1.31E-04	1.31E-04	1.31E-04
Feeding	2.18E-01	2.18E-01	2.18E-01	4.88E-05	1.15E-05	1.15E-05	4.88E-05	4.88E-05	4.88E-05	9.79E-05	9.79E-05	9.79E-05	2.89E-06	2.89E-06	2.89E-06
Microwave Pyrolysis	1.37E+02	7.27E+01	1.10E+02	1.20E-02	6.11E-03	9.62E-03	4.12E-02	2.60E-02	3.30E-02	6.48E-02	5.18E-02	5.18E-02	2.32E-03	1.53E-03	1.85E-03
Cooling	2.95E-01	3.03E-01	2.81E-01	6.70E-06	7.37E-06	6.38E-06	2.85E-05	2.31E-05	2.71E-05	6.22E-05	4.61E-05	5.92E-05	7.99E-06	5.42E-06	7.61E-06
Transport (SG, bio-oil and biochar)	1.79E+01	1.85E+01	1.56E+01	1.39E-02	1.42E-02	1.21E-02	9.42E-02	9.54E-02	8.19E-02	1.31E-01	1.33E-01	1.14E-01	6.68E-03	6.93E-03	5.81E-03
Total	2.23E+02	1.59E+02	1.93E+02	4.10E-02	2.39E-02	2.52E-02	1.51E-01	1.36E-01	1.30E-01	2.26E-01	2.15E-01	1.96E-01	9.90E-03	9.36E-03	8.57E-03
Conventional pyrolysis															
(Muñoz et al., 2017)	1.30E+03 kg CO$_2$-eq /1000 kg DM			1.40E-03 kg PO$_4^{3-}$ eq/1000 kg DM						1.35E+00 kg DCB eq/1000 kg DM					
(Wang et al., 2015)	7.37E+02 kg CO$_2$-eq /1000 kg DM			1.39E+00 kg PO$_4^{3-}$ eq/1000 kg DM			4.50E-02 kg SO$_2$ eq/1000 kg DM			1.49E+00 kg DCB eq/1000 kg DM			4.08E-03 kg C$_2$H$_4$ eq/1000 kg DM		

KP: K$_3$PO$_4$, SG: switchgrass, SiC: silicon carbide, GWP: global warming potential, EP: eutrophication potential, AP: acidification potential, HTTP: human toxicity potential, POCP: photo-oxidant formation potential

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Table 5: Economic analysis results of microwave catalytic pyrolysis scenarios for KP-300 and KP-400 cases compared with the baseline (SiC-400).

	SiC-400			KP-300			KP-400		
	Low	Base-Case	High	Low	Base-Case	High	Low	Base-Case	High
Total Production Cost (US$)	651.52	935.39	1,220	526.48	696.48	866.31	642.83	842.00	1,041
Utilities	97.02	121.34	146.03	55.98	70.01	84.26	86.78	108.53	130.62
Raw Material Costs	285.00	477.00	668.00	315.00	432.00	548.00	315.00	432.00	548.00
Operation cost	269.50	337.05	405.65	155.50	194.47	234.05	241.05	301.47	362.83
Product Sales (US$)	503.87	1,217	1,999	538.80	1,517	2,495	532.38	1,484	2,437
Bio-oil	215.76	644.25	1,073	228.27	681.58	1,135	205.76	614.38	1023
Biochar	257.31	534.63	880.57	283.11	800.92	1,320	292.36	827.10	1,362
NCG	30.80	38.52	46.36	27.43	34.31	41.29	34.27	42.85	51.58
Net Profit (US$)	-147.65	282.01	779.98	12.33	820.33	1,629	-110.45	642.33	1,395

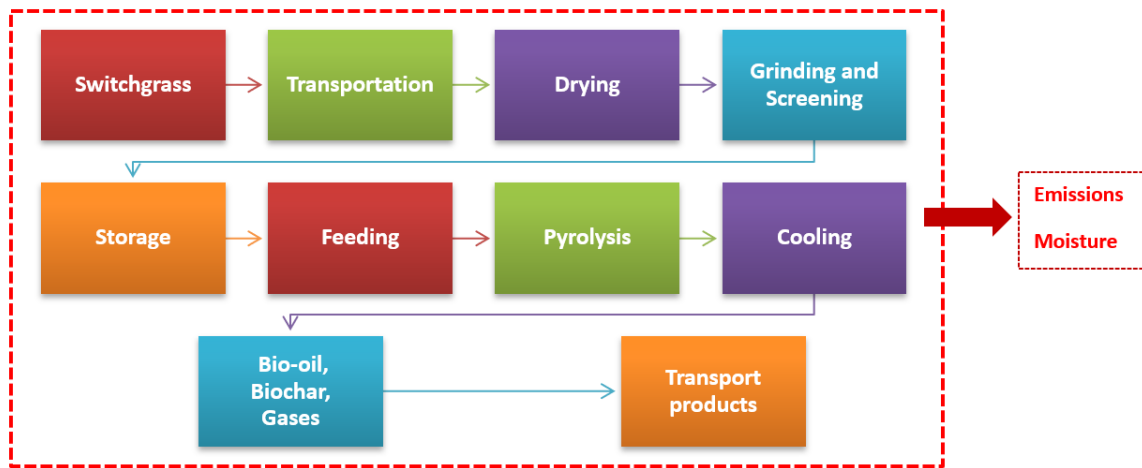KP: K_3PO_4, SiC: silicon carbide, NCG: non-condensable gases,

Figure 1. Structure of the production phenolic-rich bio-oil by microwave catalytic pyrolysis of switchgrass.
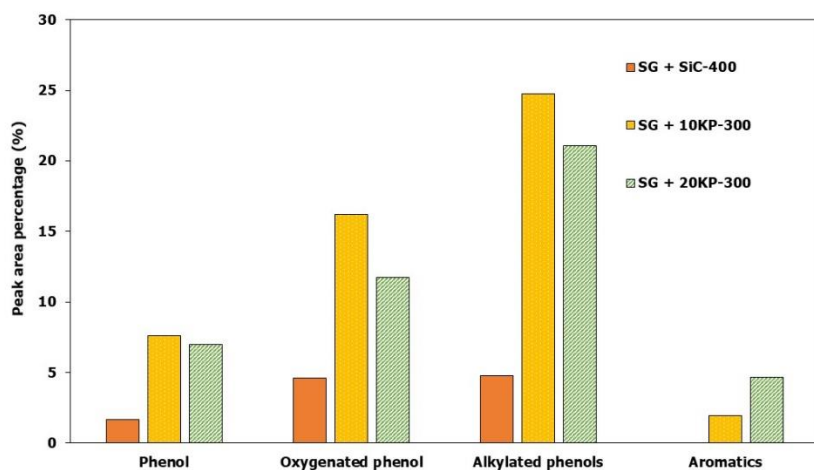
Table 2. Phenol, alkylated phenol, oxygenated phenol, and aromatic concentrations of bio-oil from microwave pyrolysis of SG for KP-300 and KP-400 cases compared with SG mixed with SiC (baseline).
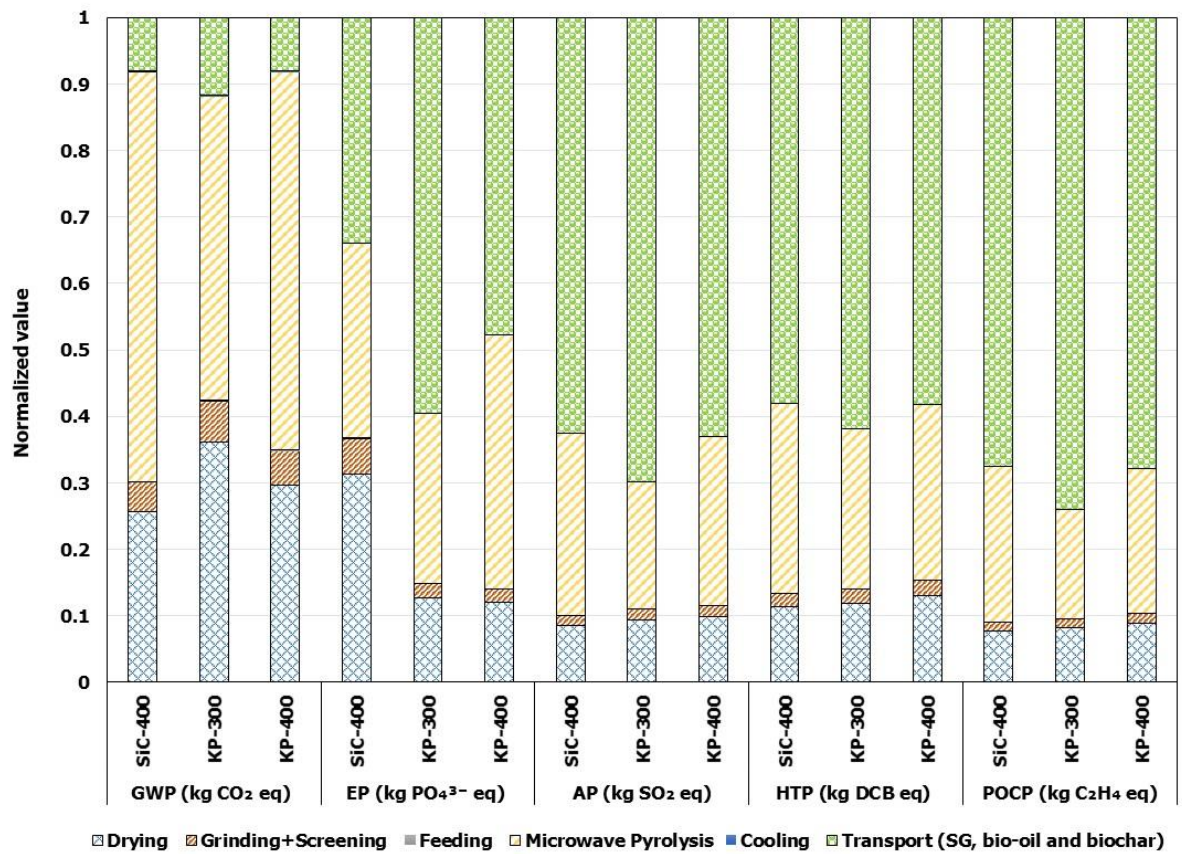
Figure 3. Breakdown of the environmental impacts of different stages involved in the microwave catalytic pyrolysis of 1000 kg dried SG for KP-300 and KP-400 cases compared with the baseline (SiC-400).
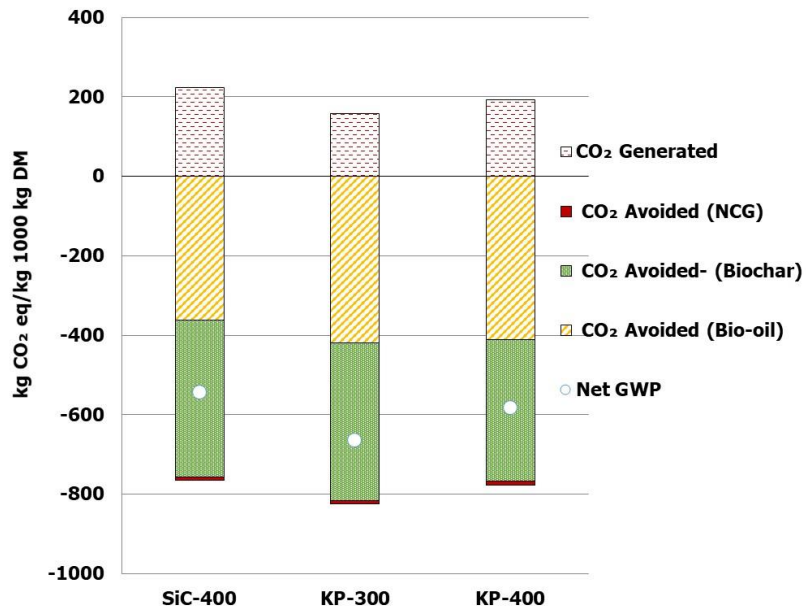
Figure 4. CO_2 generated from microwave catalytic pyrolysis and avoided CO_2 from utilizing pyrolysis products.
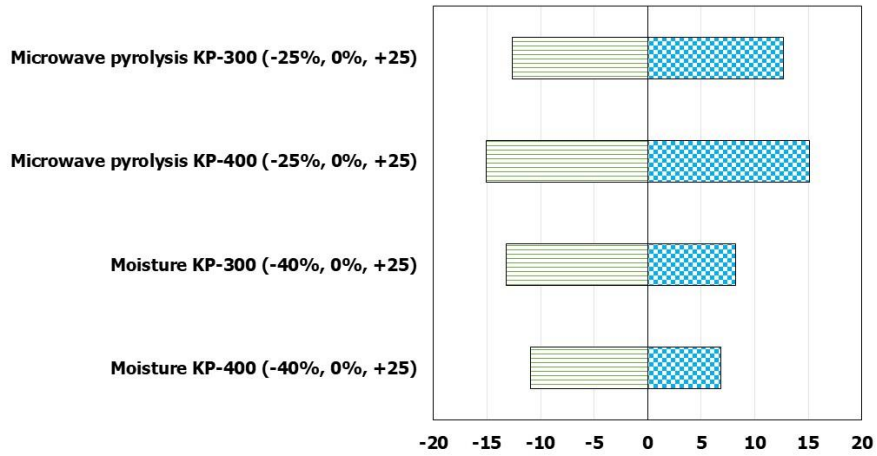
Figure 5. Sensitivity analysis of various parameters affecting GWP based on 1000 kg dried SG, and the changes are presented as percentage relative to the baseline.