Life cycle perspective of Bio-oil and biochar production from hardwood biomass; what is the optimum mix and what to do with it?

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Notation and Abbreviation List

AP: Acidification Potential

CH₄: Methane

CO: Carbon monoxide

CO₂: Carbon dioxide

EP: Eutrophication Potential

FC: Fixed carbon content

FDP: Fossil Depletion Potential

FEP: Freshwater Eutrophication

FU: Functional Unit

GHG: Greenhouse Gas

GWP: Global Warming Potential

H₂: Hydrogen

HTP: Human Toxicity Potential

ISO: International Organization for Standardisation

LCA: Life Cycle Assessment

LCCA: Life Cycle Costing Analysis

LPG: Liquefied petroleum gas

Mg: Megagram

MJ: Megajoule

N₂O: Nitrous oxide

P_k: Existing market price of potassium (K) fertilisers

P_N: Existing market price of nitrogen (N) fertilisers

P_p: Existing market price of phosphorus (P) fertilisers

PV: Present Value

SD: Standard deviation

SE: Standard error

SEE: The sum of squared errors of prediction

T: Temperature

ACCEPTED MANUSCRIPT

Abstract

Many studies identified the optimum temperature to maximise bio-oil/biochar yield using fast pyrolysis from woody biomass. However, the optimum mix of biochar and bio-oil production and their final utilisation to achieve optimal environmental and economic benefits are yet to be investigated. Hence, the aim of this study was to identify the optimum mix and utilisation using life cycle assessment and costing approach. Two utilisation scenarios were analysed: Scenario 1 considered terrestrial carbon sequestration through spreading biochar in corn fields while Scenario 2 assumed the co-combustion of biochar to displace coal in a coal-fired power station. In both scenarios, bio-oil was assumed to substitute heavy fuel oil in an industrial boiler. The functional unit used in the study was 1 Mg of green thinned logs from hardwood plantations. Scenario 1 showed outstanding greenhouse gas emissions offset (1,680 kg-CO_{2-eq} per function unit). However, this scenario lagged behind when considering other environmental impacts. Scenario 2 delivered more modest greenhouse gas offset, but it had better overall environmental and economic performance. The results indicated that the overall environmental performance of Scenario 2 decreased with increasing pyrolysis temperature due to the decline in biochar yield as well as the increased energy consumption during the pyrolysis process. Meanwhile, lifecycle cost reduced when the pyrolysis temperature increased because of the increased bio-oil production, which has higher economic value than biochar. Assuming equal weights for the environmental and economic functions, the optimal performance of Scenario 2 is likely to be achieved when the pyrolysis process is run at 500 °C with the bio-oil and biochar yields being 64% and 22%, respectively. Monte Carlo Analysis revealed that for balanced environmental and economic weights (30%-70%) the solution is robust. The Monte Carlo Analysis results suggested that under the optimal conditions, there is 97.5% likelihood that Scenario 2 would achieve 1,050 kg-CO_{2-eq} greenhouse gas emissions offset and realise \$25.8 life cycle cost savings per functional unit. This study demonstrates an easy method to incorporate life cycle assessment and costing into an optimisation decision making framework. Thus, allowing a more comprehensive assessment of policies incorporating multiple environmental impacts (criteria). It contributes to the debate about the economic and environmental validity of using forestry by-products, as well as other low cost woody biomass as a renewable energy source.

Keywords:

Biochar, Emissions reduction, Environmental and economic optimisation, Non-linear programming, Wood pyrolysis

1 Introduction

Pyrolysis is a potential pathway to extract energy and useful chemicals from biomass (Akhtar and Amin 2012). It is a relatively robust and straightforward thermochemical decomposition technology that converts biomass into bio-oil, char, and gases in the absence of oxygen (Xiu and Shahbazi 2012). Pyrolysis gas is mainly constituted of CO, CO₂, CH₄, H₂, as well as other light hydrocarbons (Sheth and Babu 2008). The gases (except CO₂) can be used as gaseous fuel or they can also be reformed into natural gas or other synthetic products (Kopyscinski et al. 2010). However, the energy density of pyrolysis gas is low, around 6 to 13 MJ kg⁻¹, and this energy is commonly used during the process (Laird et al. 2009).

Bio-oil generation through pyrolysis is a sustainable way for renewable bioenergy generation with significant GHG emissions reduction (Laird et al. 2009). That is because the CO₂ emissions generated during pyrolysis oil combustion are seen as carbon neutral because they are biogenic; that is they have been recently taken from the atmosphere by the trees and would be absorbed by photosynthesis by the next generation of trees (Fan et al. 2011). Furthermore, Lu and El Hanandeh (2017) indicated that bio-oil production through pyrolysis could even achieve greater GHG emissions saving compared to biomass fermentation for bio-ethanol production. The crude bio-oil can be simply used in existing industrial boilers for energy production (i.e. to replace heavy fuel) (Fan et al. 2011). With further hydrotreatment, the crude bio-oil can be upgraded to high-quality petroleum and petroleum products (Chang et al. 2013). The produced char can also be used as a solid fuel due to its substantial energy content (24.5 MJ/kg) (Peters et al. 2015). Apart from that, it also can be used as a soil amendment to improve the soil physiochemical properties and crop yields, while reducing GHG emissions through terrestrial carbon sequestration (Greenhalf et al. 2013). Researchers also noted that biochar can improve water use efficiency, nutrient retention in the field and reduce N₂O emissions (Peters et al. 2015). Furthermore, biochar is also an adsorbent material which may be used to remove contaminants (Park et al. 2011). Hence, the use of the final product would have direct impact on the type and magnitude of the environmental benefits realised from pyrolysis products (Peters et al. 2015). In addition to the final product applications, the environmental and economic performance of the pyrolysis systems could be affected by the relative quantity and quality of each pyrolysis product. For instance, Akhtar and Amin (2012) mentioned that several factors such as pyrolysis types, operating parameters and biomass properties will impact the yield and energy density of different pyrolysis products. Therefore, in order to achieve an optimal environmental and economic performance of the pyrolysis system, the optimum mix of products and their utilisation pathways have to be identified.

1.1 Literature review

Life cycle assessment (LCA) is a widely applied tool to evaluate the environmental performance of products and processes such as pyrolysis (Sparrevik et al. 2013). For instance, Hammond et al. (2011) and Ibarrola et al. (2012) evaluated the environmental performance of biochar for soil application and bioenergy conversion using LCA; they concluded that the biochar for soil is likely to realise higher carbon emissions reduction than using it as a bioenergy product. Peters et al. (2015) added that the use of biochar as a soil amendment on agricultural land was the most favourable option due to its ability to increase biomass yields in the crops and consequently higher GHG emission savings. However, biochar is not only beneficial for carbon sequestration but also may have other environmental benefits (Muñoz et al. 2017). Muñoz et al. (2017) studied the environmental effects of a biochar-soil system by assessing the Global Warming (GWP), Human Toxicity (HTP), Freshwater Eutrophication (FEP), and Fossil Depletion (FDP) impacts of the system. Their study showed that the avoided use of natural gas and urea had pronounced environmental benefits on FEP, FDP, and HTP. Other potential uses of biochar, including cofiring in coal power plants for power generation, use as charcoal or fuel for producing heat were assessed by Peters et al. (2015) who found that when other environmental impacts are considered, the utilisation of biochar for energy production is more favourable than its use as soil amendment. Given the conflicting results, it is difficult to conclude whether biochar dedicated to soil application or energy recovery is the better overall option.

The studies mentioned earlier focused on the environmental impacts and did not consider the economic dimension which is also an important factor in decision making. Life Cycle Cost (LCC) analysis is a tool which can be applied to integrate the economics associated with the LCA. Lu and El Hanandeh (2017) conducted a full life cycle study to compare some of the existing technologies to convert biomass into different bioenergy products. In their study, Lu and El Hanandeh (2017) included the LCC of two different pyrolysis pathways: use of pyrolysis oil for electricity generation and upgrading pyrolysis crude oil to transportation liquid fuel. The economic saving arising from the alternative product substitutions were also considered in their comparison. The results showed that using the crude bio-oil for power generation was slightly better than upgrading it to liquid fuels. However, they did not include the use of biochar as a soil amendment, as the char was assumed to be used in the process as an energy feedstock. Rogers and Brammer (2012) estimated the production cost of fast pyrolysis bio-oil with consideration of the economic value of the char. Their results showed that the reuse of char could reduce the bio-oil production cost by 18%. However, the economic value of the char was estimated based on the break-even selling price, which may not represent a realistic economic value. Interest in evaluating the economic value of the biochar is rising (Homagain et al. 2016). El Hanandeh (2011) argued that the economic profitability of biochar may vary depending on the feedstock, technology, and prevailing policies such as the availability of carbon credits or carbon

sequestration subsidies. However, these studies mainly focused on calculating the expense (i.e. production cost, feedstock cost, transportation cost, etc.), while most of them usually included incomplete cost savings from applying biochar for soil, or ignored these savings altogether. This may be attributed to the difficulties of calculating the various economic benefits from applying biochar as a soil amendment. For instance, Galinato et al. (2011), Shackley et al. (2011), and Homagain et al. (2016) only included the carbon sequestration credits in their LCC analyses. Roberts et al. (2009) developed a method to calculate the economic value of biochar based on the P and K content, the improved fertiliser use efficiency and the GHG emission reduction, which presented a more comprehensive evaluation for the biochar system. Nevertheless, the authors indicated that the uncertainty in CO₂ mitigation values was the primary variable affecting economic profit.

1.2 Research aims and objectives

The existing literature mostly focused on optimising the pyrolysis product yields (either bio-oil or biochar) by adjusting the operational parameters such as temperature, vapour residence times, size of feedstock particle sizes, heating rates, moisture content, and biomass types (Akhtar and Amin 2012). Nevertheless, the debate of which utilisation scenario (bioenergy or biochar-soil system) would yield a better economic return remains open. Meanwhile, limited efforts, incorporating both economic and environmental perspectives were made to identify the optimal utilisation and operational parameters. Therefore, this paper aims to investigate the pyrolysis product mix (bio-oil and biochar) and the utilisation scenarios (bioenergy vs biochar-soil system) that will yield optimum economic and environmental return. This objective can be achieved using the following procedure: (1) analyse the relations between different pyrolysis temperatures and product distribution using regression analysis, (2) construct scenarios for the utilisation of the pyrolysis products (3) evaluate the environmental impacts and economic performance of each scenario using a LCA and LCC approach, (4) construct economic and environmental objective functions based on the LCC and LCA results, and (5) apply unconstrained non-linear programming techniques to identify the optimum product mix and utilisation pathways that maximise the environmental and economic performance of the system.

Woody biomass is the most commonly used material for thermochemical processes because of its low ash content and high quality of the bio-oil produced (Carpenter et al. 2014). The case of the juvenile logs produced from hardwood plantation mid-rotation thinning in South-east Queensland, Australia was selected because it presents a significant problem to the hardwood plantation development. Almost half of the trees planted at the establishment phase of the plantation are removed in the first three years (first thinning), after that, another 30% are removed in the mid-rotation thinning operation after 10 to 15 years of establishment (Underhill et al. 2014). The removed thinned (small diameter)

logs have little to no commercial value due to their poor mechanical qualities and generally represent an underused resource (Underhill et al. 2014). To convert the low quality woody biomass to bio-energy or biochar may have potential to increase the profitability of the Australian forestry sector, reduce biomass wastage and satisfy the current market.

This work introduces a novel method to incorporate life cycle assessment and life cycle costing analysis with unconstrained, non-linear programming to identify the optimal solution. The method provides decision makers with a simplified visual communication tool of the overall performance of the different scenarios under consideration and identifies the optimum solution. They may also use it to gain better understanding of the effect of different policies or stakeholders' perspectives by varying the economic and environmental weightings.

2 Methods

To evaluate the environmental impacts and cost, the LCA and LCC analysis were conducted following the International Organisation for Standardisation ISO14040 (2006) and the Australian/New Zealand Standards for Life Cycle Costing AS/NZS 4536:1999 (R2014), respectively. Two scenarios were designed with different utilisation of biochar. As temperature was reported to be the most significant parameter that affects the amount and quality of the final pyrolysis products (Crespo et al. 2017), statistical regression analyses were used to establish relations between the pyrolysis temperature and pyrolysis products yields. In order to investigate the optimal economic and environmental balance, normalisation will be applied to ensure the two different objective functions can be compared on the same scale.

2.1 Regression Analysis

Statistical regression analyses were applied to predict the yield of pyrolysis products at different temperatures using published data (i.e. Horne and Williams 1996, Demirbas 2007b, Garcia-Perez et al. 2008, Abdullah and Wu 2009, Wang et al. 2009, Heo et al. 2010, Thangalazhy-Gopakumar et al. 2010, Qu et al. 2011, Liaw et al. 2012, Song and Guo 2012). The correlations between different products and pyrolysis temperature are presented in Figure 1 (a, b & c). Table 1 summarises the predicted yield function for each product from 300 °C to 600 °C.

Table 1. Empirical yield functions from fast pyrolysis of hardwood

Descriptor	Char	Bio-oil	Gas
Fitted curve (yield)	$Y = 629533T^{-1.651}$	$Y = -0.0007 T^2 + 0.7174T - 119.34$	$Y = 0.0676 T - 12.924$
R ²	0.8569	0.5574	0.4823
SE	6.78	11.61	7.64
SSE	322.68	943.25	175.45
Significance level	100%	98%	82%

where, R²: coefficient of determination; SE: Standard Error; SSE: the sum of squared errors of prediction; T: pyrolysis temperature

[Figure 1 goes here]

2.2 Economic and Environmental Analysis

The LCA presented in this study aims to calculate the environmental impacts of different scenarios via SimaPro v.8.0.4.30 modelling software (SimaPro 2017). The economic performance was calculated using LCC approach considering all the costs through the entire life stage. The economic benefits arising from final product substitutions were also taken into account. Table 2 shows the applied economic parameters and assumptions for the LCC study. The economic values were all converted to the 2018 Present Value (PV). The selection of inflation rate and discount rate were based on the Australian average data during the last ten years from Reserve Bank of Australia (2017). The LCC modelling was done in Excel™.

Table 2. Parameters used in the LCC

Parameters	Cost (Australian dollar)	Sources
P _p	\$3.78/kg	(Dairy Australia 2017)
P _k	\$1.32/kg	(Dairy Australia 2017)
P _N	\$1.37/kg	(Dairy Australia 2017)
Inflation rate	3%	(Reserve Bank of Australia 2017)
Discount rate	4.9%	(Reserve Bank of Australia 2017)
Diesel fuel cost	\$1.23/L	(Australian Institute of Petroleum (AIP) 2017)
Gasoline	\$1.25/L	(Australian Institute of Petroleum (AIP) 2017)
Natural gas	\$10/GJ (\$0.387/m ³)	(Australian Institute of Petroleum (AIP) 2017)
LPG	\$0.65/L	(Australian Institute of Petroleum (AIP) 2017)
Electricity cost	\$0.22/kWh	(Queensland Government Department of Energy and Water Supply 2018)
Carbon Price	\$29/t CO _{2-eq}	(The Treasury Australian Government 2016)
Transport cost	\$0.098/tkm	(Higgins et al. 2015)

2.2.1 Goal and scope definition

The goal of this study is to conduct a life cycle assessment and life cycle cost analysis of two utilisation scenarios of the bio-oil and biochar produced from the pyrolysis of hardwood plantation thinned logs. The LCA and LCC results will be used to formulate the objective functions in a multi-objective framework to identify the optimum mix of pyrolysis products and their prospective end-use that minimises both the environmental impacts and life cycle cost. The two distinctive scenarios analysed in this study are: energy recovery and soil-carbon sequestration. The descriptions of two scenarios are presented below.

Scenario 1:

In the first scenario, the bio-oil produced from woody biomass pyrolysis is used to substitute heavy fuel oil in an industrial boiler for energy recovery. Meanwhile, biochar will be used for carbon sequestration through application to agricultural soils (corn fields) as a soil amendment.

Scenario 2:

In the second scenario, bio-oil will be used for energy recovery, which is same as in scenario 1. Biochar will be used as energy feedstock to substitute for hard coal in a coal-fired power plant for power generation.

In both scenarios, the lifespan of bio-energy conversion plants were assumed to be 30 years. The scope of the study was limited to the South East Queensland hardwood (i.e. Gympie Messmate) plantations and the system boundaries as shown in Figure 2. The system boundaries of this study included the entire life-cycle from hardwood plantation to pyrolysis product utilisations. The hardwood plantation stage starts from seedling production through tree planation and growth to second commercial thinning. The thinned logs are then transported to the log chipping mill for preparation (size and moisture reduction). The dried wood chips are transported to the pyrolysis site which produces bio-oil, biochar and biogas. The system boundaries end at pyrolysis product applications (either being combusted for energy recovery and/or soil amendment). All the input energy and materials and output products and emissions were taken into account. Displaced products due to the end-use were counted as offset. The functional unit (FU) was referenced as the treatment of 1 Mg of logs (green) from Australian hardwood plantation mid-rotation thinning on the forest floor.

At the moment, these logs are underutilised and no viable utilisation pathways have been identified so far. Nevertheless, Venn (2005) mentioned that these low quality logs are suitable for salvage sawlogs, pulp, fibreboard, treated posts, pallets and palings. Meanwhile, Underhill et al. (2014) noted that the only large-scale viable option is to treat these logs for pulpwood if the plantation site is within 100km to a processing facility. However, Australia is now facing a glut in the pulpwood industry. Therefore, the business as usual scenario was excluded from our analysis.

[Figure 2 goes here]

According to the ISO14040 (2006), allocation procedures may be required when systems involve multiple products. If possible, system expansion should be considered first, to avoid allocation procedures (ISO14044 2006). In cases where system expansion is not feasible or appropriate, the selection of an allocation method should be made on a case-by-case basis (Ardenne and Cellura 2012). In this study, the thinned logs are treated as by-products from the hardwood plantation operation; the allocation of emissions and inputs between mature logs and thinned logs is required for the plantation phase (i.e. from plantation of seedlings up to the second thinning). According to Röder et al. (2015), the economic allocation is recommended when the values of the main product and co-product diverge greatly. As there is a wide gap between the prices of thinned logs and mature logs, economic allocation methods is used in this study. Furthermore, economic allocation is more compatible with the goal of this study as it seeks to optimise the environmental and economic functions.

2.2.2 Life cycle inventory (LCI)

The life cycle inventories of energy, materials, final products, waste, as well as emissions were taken into account in this phase. The forestry system was considered to remain in a steady state, which is in line with the existing forestry studies (e.g. Dias et al. 2007, Lu and El Hanandeh 2016). The LCI data were sourced from Eco-invent database (Ecoinvent 2016) and the Australian National Life Cycle Inventory (AusLCI 2011). The data used in this study represents the current state-of-the-art in Australia. The inventory was also used to calculate the relevant life cycle costs/revenues of each process associated with each scenario.

2.2.2.1 LCI of raw material extraction

The LCC for producing hardwood logs from mid-rotation thinning was estimated to be \$37 (2018 present value) per Mg of thinned logs by Lu and El Hanandeh (2017). The thinned logs are then delivered from site to the nearby woodchipping mill using a 45 Mg road train with an average transportation distance of 20 km (Lu and El Hanandeh 2016). For chipping 1 Mg of thinned logs, 13.6 kWh electricity and 1.23 L diesel fuel are consumed (Higo and Dowaki 2010). Furthermore, 2% of wood loss was assumed during the chipping process according to Whittaker et al. (2011).

2.2.2.2 Woodchips drying

In order to reduce the moisture content from 50% to the oven-dry basis (10 to 12%) in the green thinned logs, the woodchips are required to be dried at around 150 °C to 185 °C in continuous direct-fired dryers. For drying of hardwood logs, 3.7 GJ/m³ of energy is required (Bergman and Bowe 2011). In the current? Australian wood industry, up to 80% of the energy can be sourced from woody biomass, while the rest is supplied by electricity and natural gas (Tucker et al. 2009). The delivery of woodchips to the pyrolysis plant includes a mixture of rail and truck with an average distance of 150 km. Regarding the LCC of 1 FU of thinned logs at this stage, chipping and transportation costs approximately \$10.5 while drying processes cost around \$22.5 (Lu and El Hanandeh 2017).

2.2.2.3 Woodchips Pyrolysis

The LCIs of woodchips pyrolysis was obtained from Demirbas and Balat (2007), Fan et al. (2011) and Peters et al. (2015). The energy inputs and obtained yields varied along with the changing temperatures. In this study, the required energy input to reach the different temperatures was estimated based on the wood enthalpy value according to Daugaard and Brown (2003). The details of the energy requirement (i.e. enthalpy) per function unit during woodchips pyrolysis at different temperatures are calculated and presented in Table 3.

Table 3. Energy consumptions during wood pyrolysis from 300 to 600 °C (calculated based on Daugaard and Brown (2003))

Temperature (°C)	Specific heat (kJ/kg K)	Enthalpy (kWh)
300	1.94	113.17
350	2.06	140.19
400	2.18	169.56
450	2.3	201.25
500	2.43	236.25
550	2.55	272.71
600	2.67	311.5

The capital cost for a medium size fast pyrolysis plant was estimated using the following equation (1) which is suggested by Bridgwater (2012) and Hayward et al. (2015):

$$K_{AUD \text{ million } 2012} = 2.302 \times f^{0.67} \dots (1)$$

Where,

K: capital cost of the pyrolysis plant

f : biomass annual input rate (Mg, dry)

The annual biomass input rate was estimated to be 30,000 Mg (dry) according to Lu and El Hanandeh (2017). The capital cost was then calculated as \$26 million Australian dollars in 2018 value. The annual cost of operation and maintenance (O&M) were estimated at 3 million according to Hayward et al. (2015).

2.2.2.4 Economic value of pyrolysis products

The economic value of biochar as a soil amendment

The revenues of char from bio-oil and biochar substitution were considered within the system boundaries. The economic value assigned to the biochar was calculated in this study following the recent study from Roberts et al. (2009). The estimated economic value was based on three components, which includes (1) the economic value of phosphorus (P) and potassium (K) nutrient content, (2) the improved fertiliser use efficiency, and (3) the economic benefit caused by GHG emissions reduction from applying biochar. Therefore, the value of biochar (V_{biochar}) can be calculated by the equation (2):

$$V_{\text{biochar}} = P_P \times qc_P + P_K \times qc_K + a \times e (P_P \times q\text{Base}_P + P_K \times q\text{Base}_K + P_N \times q\text{Base}_N) + P_{\text{GHG}} \times q_{\text{GHG}} \dots (2)$$

Where,

P_P = the existing market price of P,

qc_P = the quantity of P in biochar,

P_K = the existing market price of K,

qc_K = the amount of K in biochar,

a = the conversion factor (0.14 ha t⁻¹ of biochar was assumed according to Roberts et al. (2009)),

e = the improved fertiliser use efficiency (in this study, $e = 7.2\%$ was assumed based on Roberts et al. (2009)),

$q\text{Base}_P$, $q\text{Base}_K$, $q\text{Base}_N$: the amounts of 'P' and 'K' fertilisers applied under base circumstances. In this study, the average fertiliser application rates were assumed to be 154.4, 64.9, and 94.0 kg ha⁻¹ for N, P₂O₅, and K₂O for corn, respectively according to Roberts et al. (2009),

P_N = the existing market price of N fertiliser,

P_{GHG} = the economic benefit arising from GHG emission reductions, and

q_{GHG} = the amount of GHG emissions reductions by applying biochar.

The carbon offset in this study was calculated based on the life-cycle GHG emissions reductions. Evidence shows that biochar produced at high temperatures contains a higher percentage of fixed carbon, which also increases the calorific value (El Hanandeh 2013). Demirbas (2007a) found a highly significant linear correlation between the woody (hardwood) biomass pyrolysis temperature and the fixed carbon content in biochar. Therefore, Equation (3) was applied to calculate the amount of fixed carbon in biochar.

$$FC (\%) = 0.037T + 55.86 \dots (3)$$

Where, FC = fixed carbon content (%) in biochar

T = temperature (K)

Furthermore, although pyrolysis temperature has a significant impact on the characteristics of produced biochar, research studies showed no significant effect of pyrolysis temperature on N contents of biochar (Wang et al. 2015). Hence, we assumed that the N content in biochar remained 0.34% according to Wang et al. (2015). In addition, the K and P content in biochar increase with the higher pyrolysis temperature (Peng et al. 2011). However, according to the finding from Wang et al. (2015), the changes of K and P content in biochar produced at different temperatures were negligible due to the small amount of K and P content. Furthermore, this study assumed that all P and K in the biochar would be mineralised in soil eventually (Frank 2008). Therefore, the K and P content in biochar from wood were assumed as 0.02% and 0.04% according to Wang et al. (2015).

The economic value of pyrolysis products as energy feedstock

In regard to the final product substitutions, the energy density of char is usually higher than that of coal, while bio-oil has lower energy density compared to that of fossil crude oil. Nevertheless, the perfect substitutions of two related products were assumed according to Yoder et al. (2011). Therefore, the economic values per unit of energy of bio-oil and heavy fuel are equal, while the same assumptions were made for biochar and coal. In addition, the pyrolysis gas will be used for maintaining the process (Peters et al. 2015). The value of the excess gas energy was assumed to be used for replacing natural gas (Lu and El Hanandeh 2017). Therefore, the economic values of pyrolysis products were estimated based on their energy (calorific) content in our study.

The calorific content of bio-oil (equation 4) and biochar (equation 5) was calculated based on the regression investigated by Yoder et al. (2011). The energy content of pyrolysis gas was calculated using equation (6) Kan et al. (2016) and the data sourced from Horne and Williams (1996).

$$\text{Bio-oil Calories (MJ/kg)} = 17.85 + 0.0075 T \text{ } ^\circ\text{C} \dots (4)$$

$$\text{Biochar Calories (MJ/kg)} = 16.2 + 0.02678571 T \text{ } ^\circ\text{C} \dots (5)$$

$$\text{Gas Calories (MJ/m}^3\text{)} = 107.98 \times \text{H}_2 + 126.36 \times \text{CO} + 358.18 \times \text{CH}_4 + 59.036 \times \text{C}_2\text{H}_4 + 63.772 \times \text{C}_2\text{H}_6 / 1000 \dots (6)$$

Table 4 shows the calculated quantities of pyrolysis products at different temperatures. In addition, the economic values of pyrolysis energy products and soil amendment products from 300 to 600 °C are also presented.

Table 4. Economic values (2018 present value) of pyrolysis products from temperature 300 to 600 °C based on 1 FU of thinned logs

Temp (°C)	Bio-oil yield (wt %)	Char yield (wt %)	Gas yield (wt %)	Carbon in char (wt %)	Total Gas energy (MJ)	Total Stored CO ₂ (kg) by char	Char value as soil amendment (\$)	Char value as energy feedstock (\$)	Bio-oil value (\$)	Gas value (\$)
300	32.76	51.20	7.36	66.96	566	1258	32	42	60	20
350	45.86	39.70	10.74	68.81	827	1002	27	34	85	29
400	55.46	31.84	14.12	70.66	1,087	826	23	29	105	38
450	61.56	26.22	17.50	72.51	1,347	698	20	25	119	47
500	64.16	22.03	20.88	74.36	1,607	601	18	22	126	57
550	63.26	18.82	24.26	76.21	1,868	526	17	20	127	66
600	58.86	16.30	27.64	78.06	2,128	467	16	18	120	75

2.2.3 Life cycle impact assessment (LCIA)

The LCIA phase aims to evaluate the significance of potential environmental impacts by using the results from the LCI phase (ISO14040 2006). The choice of environmental impact categories to be evaluated usually depends on the goal and scope of the study (ISO14040 2006). Five environmental impact categories were selected based on the Best Practice Guide to Life Cycle Impact Assessment in Australia (Grant and Peters, 2016), including Global warming (GWP), acidification (AP), eutrophication (EP), fossil depletion (FDP) and human toxicity (HTP) potential.

The selection of LCIA methods is based on which environmental issues are required for a particular LCA study (ISO14044 2006). There are several LCIA methods specific for the Australian region, including Eco-indicator with Australian adjustment; CML 2 baseline 2001-Australian toxicity factor; EDIP with Australian substance; and Impact 2002+ with Australian substance added (Bengtsson and Howard 2010b). In this study, the CML2001 life cycle impact assessment method was selected for characterising different emissions into the relevant environmental impact categories as suggested by the newly published Best Practice Guide for Mid-Point Life Cycle Impact Assessment in Australia (Renouf et al. 2016).

2.3 Optimisation

In order to calculate the overall performance of each scenario from both environmental and economic perspectives, LCA and LCC results have to be incorporated into a multi-objective function (i.e. minimising environmental impact and minimising the life cycle cost). Hence, an unconstrained, non-linear programming approach was used to construct the objective function. Non-linear programming was used to account for the non-linearity in the system as revealed by the regression analysis. No constraints were applied to how much biomass should be allocated to any of the scenarios or how much can be produced of any product because there are no physical, legislative or market constraints that limit the use of the biomass or the pyrolysis products.

A two-stage normalisation was needed to convert the LCA results to a scale consistent with the normalised LCC results. The first step included converting all impact categories to one normalised impact indicator using the Impact 2002+ points method adjusted to Australian conditions. In this stage, the normalised impact category value was calculated as the ratio of the LCIA value per FU to the total impact emissions per person per year in Australia according to Jolliet et al. (2003) and Huppes and van Oers (2011). The impact indicator which represents the overall environmental performance of the scenario is then calculated as the sum of all normalised impact categories.

In the second step, in order to convert the multi-objective optimisation problem to a single objective optimisation problem, normalisation is applied to both economic and environmental objective functions, so that categories with different units could be compared on the same scale. This step is done by calculating the ratio of the impact indicator obtained for each temperature in each scenario and the optimal impact indicator (absolute value) in the set to arrive at a value ≤ 1 (Islam et al. 2015). The LCC values were also normalised in the same manner as the second step in LCA normalisation but using the LCC optimal value. This is necessary to prevent scale bias. After that, the weighted sum approach is used to combine the two objective functions into a single objective problem with a scalar

objective function. The entire optimisation process is done in the Excel spreadsheet. Equation 7 presents the objective function used to evaluate the performance of the scenarios.

Overall performance = Environmental weighting $\times$ normalised LCA value + Economic weighting $\times$ normalised LCC value ... (7)

where, Environmental weighting + Economic weighting = 1

An example of optimisation procedure is presented in the Appendix B to better clarify the process.

3 Results and Discussions

Table 5 presents the LCA and LCC results of the two scenarios. The results show that both scenarios would yield environmental benefits as indicated by the negative sign of the impact values, particularly the GWP, ADP, and FDP. Energy consumption from fossil fuel was the main contributor to the environmental burdens. Woodchips drying accounted for ~38% of the total fossil fuel consumption while the pyrolysis process accounted for ~34% and transportation process accounted for ~22%, the remaining ~6% was accounted for by plantation establishment and thinning processes, in both scenarios. The actual energy consumption percentages may slightly change due to the different pyrolysis temperatures. However, the impacts of fossil fuel consumption were largely mitigated by the offset gained from the end-use of the pyrolysis products to displace fossil fuel and/or synthetic fertilisers.

Table 5. Life cycle impacts and costs for each scenario

Impact category	Units/FU	Australian per capita	Scenario	300 °C	350 °C	400 °C	450 °C	500 °C	550 °C	600 °C
GWP	kg CO ₂ eq	28,690	Scenario 1	-1670	-1568	-1480	-1360	-1270	-1190	-1100
			Scenario 2	-1240	-1180	-1130	-1070	-1010	-980	-930
AP	kg SO ₂ eq	123	Scenario 1	-0.26	-0.74	-1.11	-1.36	-1.5	-1.51	-1.4
			Scenario 2	-17.7	-15	-13.1	-11.8	-10.7	-9.69	-8.79
EP	kg PO ₄ eq	19	Scenario 1	0.15	0.073	0.005	-0.022	-0.04	-0.05	-0.03
			Scenario 2	-0.99	-0.85	-0.77	-0.70	-0.64	-0.58	-0.51
FDP	kg Oil eq	6,231	Scenario 1	-52.9	-118	-169	-205	-227	-231	-219
			Scenario 2	-337	-350	-365	-375	-376	-364	-339
HTP	kg 1,4-DB eq	3,216	Scenario 1	29.2	-2.65	-27.5	-45	-54.6	-55.9	-48.6
			Scenario 2	-478	-417	-378	-348	-321	-294	-264
Normalised overall LCA	unit/FU		Scenario 1	-0.052	-0.077	-0.096	-0.107	-0.112	-0.111	-0.102
			Scenario 2	-0.442	-0.394	-0.363	-0.338	-0.316	-0.293	-0.267
LCC	\$/FU		Scenario 1	\$13.14	-\$6.64	-\$23.06	-\$35.38	-\$42.95	-\$45.53	-\$42.64
			Scenario 2	\$5.77	-\$12.29	-\$27.47	-\$38.85	-\$45.68	-\$47.65	-\$44.27

3.1 LCA and LCC results of the two scenarios

Considering climate change impact, Scenario 1 shows better performance than Scenario 2 as indicated by the GWP values. This can be attributed to the massive potential of carbon sequestration in the biochar soil system (i.e. terrestrial carbon sequestration), which could offset 1268 kg CO₂-eq/FU for the biochar produced at 300 °C. However, this benefit decreases with increasing pyrolysis temperature due to increased energy consumption and reduced biochar yield; for example when pyrolysis temperature increases from 300 to 600 °C, the biochar yield decreases from 51.2% to 16.3 %, and the energy input required for the production increases from 113.17kWh/FU to 311.5kWh/FU. This result is in line with other LCA studies such as Hammond et al. (2011) and Ibarrola et al. (2012). However,

when considering other impact categories, Scenario 1 showed lower environmental benefits than Scenario 2, particularly on AP, EP, HTP and FDP. These results can be explained by the fact that the power grid in Queensland is highly dependent on fossil fuel, especially coal. Therefore, co-firing the biochar in a coal power plant would reduce the amount of coal used in the plant, thus reducing the associated impacts.

Since the LCIA results present conflicting performances in the different environmental impact indicators, it is necessary to normalise the data for a more equitable comparison. When considering the normalised environmental performance (shown in Table 5), it becomes apparent that Scenario 2 had the best environmental performance at 300 °C. However, the environmental performance of Scenario 2 declined as the pyrolysis temperature increased, which was linked to decreasing biochar production and increased energy input to the system. This result also indicated that the emission savings from biochar substitution for coal were more significant compared to that of bio-oil substituting heavy fuel in a power station. This finding is particularly significant as the Australian and world economy is shunning coal in favour of renewable and low carbon energy sources. Therefore, the environmental benefits gained from this scenario are likely to reduce in the future as the grid becomes less carbon intensive. On the other hand, the normalised overall environmental performance of Scenario 1 correlated well with the bio-oil production rate, which suggested that the emission savings (other than GHG emissions) were caused by the bio-oil substitution to fossil fuels. Although Scenario 1 had greater GHG emission reduction compared to Scenario 2 (varying between 18 to 35% depending on the different pyrolysis temperatures), the biochar-soil system realised lower overall environmental performance than the case of biochar being used as energy to displace coal.

Regarding economic performance; the feedstock cost, capital cost & decommissioning cost and the O&M cost are the three most significant contributors, which present ~38% and ~16% and ~36% of the total expenditure, respectively. Meanwhile, the transportation cost only accounted for less than 10%. Bio-oil is the biggest source of revenue contributing 55% to 70% (depends on the pyrolysis temperature) of the total revenue in both scenarios. Meanwhile, the economic benefits associated with pyrolysis gas accounted for 5% to 18% and are mainly due to displacement of natural gas use within the pyrolysis process. The biochar accounted for 10% to 33% of total revenue in Scenario 1; meanwhile, biochar yielded a slightly higher contribution (11-39%) to revenue in Scenario 2.

By investigating the economic performance at different temperatures, the LCC of the two scenarios showed a similar trend. Both yielded positive cost (i.e. expenditure) at 300 °C, but the costs declined as the temperature increased and soon yielded negative costs (i.e. revenue) once the temperature exceeded 350 °C. The lowest LCC would be observed between 500 and 550 °C for both scenarios. For the entire temperature range considered in this study, Scenario 2 showed relatively lower LCC than

Scenario 1. In other words, the economic returns from the biochar-soil system are less than that of using the char for energy generation. Although Scenario 1 had the potential to generate a higher economic return from carbon credit, the low commercial value of biochar as a soil amendment resulted in a lower overall economic return. Biochar as an energy feedstock is a more valuable product from an economic point of view. The most significant economic benefits may be realised at around 550 °C for each of the two scenarios. Beyond 550 °C, the LCC increased due to the reduction in the yields of biochar and bio-oil. Although the pyrolysis gas production rate increased, the economic benefits from the gas substitution were far less than the char and bio-oil. Additionally, the gap between the LCCs of the two scenarios also decreased after 550 °C.

Government policies and regulations may affect the viability of the bioenergy conversion sector. For instance, in 2015 the Queensland state government set up a goal to explore the state's biofuels potential in order to achieve a clean energy future. Currently, the Queensland Government is cooperating with the bioenergy industry sector to develop initiatives, which could significantly encourage biofuel production and consumption (State of Queensland, 2015). Our results have highlighted the importance of taking a more rounded approach to policy setting as the focus on a single objective or criteria may be counterproductive as shown in the case of terrestrial sequestration of biochar which can yield higher GHG emission offset, albeit at lower overall environmental and economic benefits. This is extremely important for the State of Queensland as well as other Australian and international states that are pursuing to achieve GHG emissions reductions targets through implementing policies that may favour or encourage certain utilisation of the resources.

3.1 Optimal Overall Performance

Scenario 2 shows better LCA and LCC outcomes than Scenario 1. Nevertheless, for the sake of completeness, both scenarios were analysed. However, choosing the optimal pyrolysis temperature is less straightforward because of the conflicts between the LCC and LCA results. Any solution will involve a compromise between the environmental performance and the LCC. This compromise may be presented as weights in an equation combining the two objectives. To overcome the issue of incommensurate units, normalisation was used as explained earlier in section 2.3.

Figure 3 (a) and (b) presents the normalised overall performance for the two scenarios over the temperature range 300 °C to 600 °C. Scenario 1 lagged in performance behind Scenario 2 for the entire temperature range and weighting factors. The best overall performance for Scenario 1 can be realised at 550 °C when the economic weighting was >10%. In the case of Scenario 2, the optimal pyrolysis temperature to achieve maximum performance is 500 °C when the economic weighting is between 20% and 50%. When economic weightings exceeding 50%, the optimal overall performance

of Scenario 2 can be achieved at 550 °C; thus indicating noticeable sensitivity to the weighting assigned to each objective function. However, at around 450 °C, the performance of Scenario 2 seems to be indifferent to the weight assigned to either of the objective functions. Therefore, the pyrolysis temperature of 450 °C may offer the best compromise and as such a more robust solution.

[Figure 3 goes here]

3.2 Monte Carlo Analysis

Variability in the assumptions and LCI data in this study may cause uncertainties in the results. Hence, these uncertain factors were identified, and their effect on the stability of the final solution was analysed in this section. Transportation distance, fixed carbon content, energy values of pyrolysis products and energy consumption were considered the most uncertain factors in both the LCA and LCC analysis. In addition, the uncertainties in the carbon price, inflation rate, discount rate, as well as the capital and O&M costs are also causing of concern in the LCC. Monte Carlo Analysis (1000 simulations) were conducted in SimaPro v.8.0.4.30 and Excel spreadsheet model. The parameters and their distribution types are summarised in Table 6.

Table 6 Parameters assessed in the Monte Carlo Analysis

Parameter	Mode	Unit	Distribution type
Haul distance	100	%	Normal: $\mu=100$, $\sigma=20$
Energy consumption	100	%	Normal: $\mu=100$, $\sigma=20$
Fixed carbon content	100	%	Normal: $\mu=100$, $\sigma=30$
Energy value of bio-oil, gas, and char	100	%	Normal: $\mu=100$, $\sigma=20$
Inflation rate	3.0	%	Normal: $\mu=3.0$, $\sigma=2.0$
Discount rate	4.9	%	Normal: $\mu=4.9$, $\sigma=2.0$
Capital and O&M cost	100	%	Normal: $\mu=100$, $\sigma=30$
Carbon price	29	\$/Mg CO ₂ eq	Triangle: Min=23; Max=31

Distribution types were estimated based on our previous research (Lu et al. 2017). Normal distribution was assumed for transportation distance, energy consumption, fixed carbon content in char, the energy value of pyrolysis product, capital and O&M cost because of a lack of specific data to support the minimum and maximum limits. The mean and standard deviation for energy consumption,

transportation distance, capital and O&M cost were estimated from the coefficient of variation given in the literature as discussed in our previous study (Lu and El Hanandeh 2017). The coefficient of variation, mean and standard deviation for the energy values of pyrolysis products and fixed carbon content were assumed based on the study by El Hanandeh (2013). The Normal distribution was also assumed for the inflation rate, discount rate by downloading the time series from the Reserve Bank of Australia. For the carbon price, a triangular distribution was selected to ensure that upper and lower limits could be specified.

The detailed results from the Monte Carlo analysis for the LCA are presented in Appendix A. Figure 4 (a) and (b) show the impact on the overall uncertainties on environmental performance. Our results show that Scenario 1 had higher sensitivity to the overall uncertainties in all environmental impact categories, which was mainly attributed to the high sensitivity of fixed carbon content in biochar. The effects of the combined uncertainties in Scenario 1 are more prominent compared to Scenario 2, particularly on the EP and HTP. In Scenario 2, the effects of the overall uncertainties were relatively low; the coefficients of variation were mostly below 10% in all impact categories. In addition, except for the GWP, all other impact indicators in Scenario 2 were better than Scenario 1 for all investigated temperature ranges. The analysis results also indicated that the overall performance of Scenario 2 was better than Scenario 1. Furthermore, the best environmental performance for Scenario 2 was still most likely to be realised at 300 °C. Meanwhile, the optimal temperature to achieve best environmental performance in the case of Scenario 1 was most likely between 450 and 550 °C.

[Figure 4 goes here]

The Monte Carlo Analysis results for the LCC at different temperatures are presented in Table 7. As evident in the table, the overall performance was not significantly affected. Scenario 2 continued to be the leading option from the economic point of view. Although the standard deviations and confidence intervals in Scenario 2 showed higher variation than Scenario 1, the 97.5th percentile still indicated that Scenario 2 had lower LCC than Scenario 1. In addition, Scenario 2 continued to present the best performance at approximately 550 °C, which was in line with the original LCC result.

Table 7. Economic performance of each scenario under uncertainty conditions

Temp	300 °C		350 °C		400 °C		450 °C		500 °C		550 °C		600 °C	
Scenario	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Mean	41.5	-1.3	37.5	-9.2	29.6	-25.4	27.8	-32.7	26.5	-35.3	24.9	-39.2	27.7	-34.8
SD	6.9	11.6	6.5	11.7	8.0	15.6	7.6	14.4	7.1	13.0	8.0	15.1	7.2	14.1

97.5th percentile	45.1	12.9	45.9	11.0	32.5	2.1	48.3	-17.6	47.0	-25.8	27.9	-27.5	49.4	-24.2
E	1.2	2.3	1.3	2.4	1.5	3.0	1.4	2.8	1.4	2.8	1.6	3.2	1.4	2.9

*E: confidence interval (95%), SD: standard deviation

Figure 5 and Table 8 present the Monte Carlo Analysis result of Scenario 2. Regarding the overall performance, the Monte Carlo Analysis result showed that to achieve the optimal overall performance, the temperature for fast pyrolysis should stay around 500 °C when the environmental and economic weightings range from 30% to 70%. Although the standard deviations showed large variability, the 97.5th percentiles (shown in Table 8) indicated that when the temperature reached 500 °C, Scenario 2 had higher chances to achieve the best performance compared to 450 and 550 °C. This result is also in line with our original outcomes.

Table 8. Monte Carlo Analysis on the overall performance – Scenario 2

Environmental: Economic	Temperature	300 °C	350 °C	400 °C	450 °C	500 °C	550 °C	600 °C
50%:50%	Mean	-0.25	-0.35	-0.38	-0.41	-0.42	-0.40	-0.38
	SD	0.20	0.11	0.13	0.11	0.10	0.11	0.11
	97.5 th percentile	0.14	-0.01	-0.13	-0.19	-0.22	-0.20	-0.17
30%:70%	Mean	-0.16	-0.28	-0.38	-0.43	-0.45	-0.44	-0.42
	SD	0.23	0.21	0.17	0.15	0.13	0.14	0.14
	97.5 th percentile	0.35	0.13	-0.05	-0.15	-0.19	-0.17	-0.15
70%:30%	Mean	-0.328	-0.350	-0.376	-0.383	-0.380	-0.361	-0.336
	SD	0.14	0.11	0.09	0.08	0.07	0.07	0.07
	97.5 th percentile	-0.06	-0.14	-0.20	-0.23	-0.24	-0.22	-0.20

[Figure 5 goes here]

3.3 Limitation and Recommendations

The LCI data used and assumptions made in this study were based on the South-east Queensland region. The availability and accuracy of the used data may also have imposed limitations on the accuracy of the analysis. Furthermore, this paper assumed that the forestry system was in a steady state. Therefore, all the carbon emissions caused by woody biomass combustion were assumed to be absorbed by the future timber plantation. However, this assumption only makes sense when carbon sequestration rate of the future timber plantation is equal to or greater than the rate of carbon released

from woody biomass combustion. Furthermore, the GWP in the entire study was accounted using 100 years interval, which is commonly applied in the LCA studies. However, selecting a different time horizon would affect the numerical values obtained for carbon dioxide equivalents.

The environmental impact categories considered in this study were limited to GWP, AP, EP, FDP, and HTP, which have been recommended for the Australian situation. Other environmental impact categories were not included. However, if applying this study to other regions, the selection of the assessed environmental impact categories should be reconsidered to suit their local characteristics.

In addition, the utilisation of bio-oil was only considered as a substitute for heavy fuel oil, while other applications were not considered. The biochar for soil amendment option was assumed to be used in corn fields. However, the environmental and economic benefits from biochar applications in different crops may vary. In addition, other potential benefits of biochar such as heavy metal absorption and liming effect were not included in the biochar for soil system because realising such benefits is highly dependent on the soil properties and the crop in question. In the LCI phase, the required energy input to reach the different temperatures was estimated based on the specific heat, which could not reflect the actual energy consumption as these are process/equipment dependent. Furthermore, the pyrolysis products were assumed to be perfect substitutes for fossil fuel with adjusted value based on their energy density. Although this is a common and convenient assumption, there are differences between the characteristics and properties of the types of fuel which may require operational adjustments or modification to the boiler and the power plant. However, these are likely to be a small fraction of the overall operational and maintenance cost. Notwithstanding that, purpose built industrial boilers which can operate using bio-oil and biomass are now available on commercial scale.

The weighting assigned to each of the objectives (economic vs environmental) is an important factor which may affect the final results (Islam et al. 2015). It is recommended that a study solicits weights from relevant stakeholders to be conducted. In this study, the impact of weighting was tested by varying the weight assigned to each objective function and re-running the model.

4 Conclusions

Temperature is an important parameter that affects pyrolysis products yields. Many researchers focused on investigating maximising production rates of pyrolysis oil and char by adjusting the pyrolysis temperature. However, yield is not the only factor affecting the environmental and economic performance of products. The qualities of the products and their final application have direct impact on their environmental impacts and economic value. The aim of this study was to identify the optimum pyrolysis product mix (biochar and bio-oil) and end-use that minimise the life cycle environmental impacts and cost of managing the thinned logs from hardwood plantations in South

East Queensland. Two end-use scenarios (energy recovery and soil application) were considered. Under each scenario, seven product mixes (covering pyrolysis temperature range between 300 and 600 °C) were analysed. The LCA and LCC results indicated that soil application of biochar is an effective measure to combat climate change. However, using biochar to substitute coal in a coal-fired power station has lower overall environmental impacts and lifecycle cost. The exact mix to achieve the optimum performance showed some sensitivity to the weightings assigned to the economic and environmental objectives. Nevertheless, Monte Carlo Analysis revealed that there is 97.5% likelihood that the optimal environmental and economic benefits can be achieved by running the pyrolysis process at 500 °C (bio-oil yield 64%, biochar 22%) when considering realistic economic weights (30 to 70%) in the objective function. The results of this study present a strong case for the use of pyrolysis for bio-energy production from the low-value woody biomass. The results may also be relevant to other under-utilised biomass, such as agricultural wastes. Globally, this study is a small yet significant contribution towards the achievement of the United Nations Sustainable Development Goals, specifically under the Affordable and Clean Energy; Climate Action and Responsible Consumption and Production. Furthermore, incorporating environmental life cycle assessment and costing into a multi-objective optimisation framework gives decision makers a more rounded view of the effectiveness of policies proposed to combat climate change or achieve renewable energy targets.

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Appendix A. Monte Carlo analysis results in LCA for the two scenarios

Scenarios	Temp	Impact	Units/FU	Mean $\pm$ E*	SD*	97.5 th percentile	CoV*
Scenario 1	300 °C	GWP	kg CO ₂ eq	-1740 $\pm$ 25	203	-1700	11.6%
		AP	kg SO ₂ eq	-0.26 $\pm$ 0.01	0.094	-0.092	35.6%
		EP	kg PO ₄ eq	0.143 $\pm$ 0.001	0.017	0.175	11.9%
		FDP	kg Oil eq	-54 $\pm$ 0.79	12.7	-30.7	23.4%
		HTP	kg 1,4-DB eq	28.9 $\pm$ 0.41	6.61	-41.4	22.3%
Scenario 2	300 °C	GWP	kg CO ₂ eq	-1280 $\pm$ 7.07	114	-1250	8.90%
		AP	kg SO ₂ eq	-17.7 $\pm$ 0.09	1.48	-15	8.40%
		EP	kg PO ₄ eq	-0.99 $\pm$ 0.01	0.098	-0.81	10%
		FDP	kg Oil eq	-338 $\pm$ 1.69	27.2	-285	8.05%
		HTP	kg 1,4-DB eq	-477 $\pm$ 2.7	43.6	-398	9.16%
Scenario 1	350 °C	GWP	kg CO ₂ eq	-1590 $\pm$ 19.28	171	-1560	10.8%
		AP	kg SO ₂ eq	-0.74 $\pm$ 0.01	0.13	-0.50	17.5%
		EP	kg PO ₄ eq	0.071 $\pm$ 0.01	0.022	0.11	30.5%
		FDP	kg Oil eq	-119 $\pm$ 1.07	17.2	-152	14.5%
		HTP	kg 1,4-DB eq	-3.23 $\pm$ 0.55	8.94	14.2	277%
Scenario 2	350 °C	GWP	kg CO ₂ eq	-1220 $\pm$ 19.83	88.1	-1230	7.22%
		AP	kg SO ₂ eq	-15 $\pm$ 0.01	1.16	-12.7	7.73%
		EP	kg PO ₄ eq	-0.86 $\pm$ 0.0013	0.078	-0.71	9.11%
		FDP	kg Oil eq	-352 $\pm$ 1.03	26	-302	7.37%
		HTP	kg 1,4-DB eq	-418 $\pm$ 0.54	34.8	-349	8.3%
Scenario 1	400 °C	GWP	kg CO ₂ eq	-1520 $\pm$ 16.05	153.52	-1510	10.1%
		AP	kg SO ₂ eq	-1.11 $\pm$ 0.01	0.16	-0.82	14.5%
		EP	kg PO ₄ eq	0.0145 $\pm$ 0.002	0.026	0.0642	179%
		FDP	kg Oil eq	-170 $\pm$ 1.26	20.3	-129	12%
		HTP	kg 1,4-DB eq	-28.2 $\pm$ 0.68	11	-7.85	39%
Scenario 2	400 °C	GWP	kg CO ₂ eq	-1130 $\pm$ 5.73	79.1	-1160	7%
		AP	kg SO ₂ eq	-13.2 $\pm$ 0.06	0.98	-11.2	-7.42%
		EP	kg PO ₄ eq	-0.77 $\pm$ 0.004	0.068	-0.64	8.81%
		FDP	kg Oil eq	-366 $\pm$ 1.61	25.9	-316	7.08%
		HTP	kg 1,4-DB eq	-379 $\pm$ 1.85	29.9	-319	7.91%
Scenario 1	450 °C	GWP	kg CO ₂ eq	-1420 $\pm$ 12.71	133.48	-1390	9.4%
		AP	kg SO ₂ eq	-1.51 $\pm$ 0.01	0.20	-1.14	13 %
		EP	kg PO ₄ eq	-0.047 $\pm$ 0.002	0.031	0.015	66.7%
		FDP	kg Oil eq	-207 $\pm$ 1.43	23	-163	11.1%
		HTP	kg 1,4-DB eq	-55.5 $\pm$ 0.82	13.2	-30.2	24%
Scenario 2	450 °C	GWP	kg CO ₂ eq	-1120 $\pm$ 5.63	77.1	-1140	6.88%
		AP	kg SO ₂ eq	-11.8 $\pm$ 0.05	0.86	-10.1	7.26%
		EP	kg PO ₄ eq	-0.70 $\pm$ 0.004	0.061	-0.58	8.71%

Scenario 1	500 °C	FDP	kg Oil _{eq}	-375±1.64	26.4	-324	7.03%
		HTP	kg 1,4-DB _{eq}	-348±1.67	27	-296	7.77%
		GWP	kg CO ₂ _{eq}	-1380±9.11	92.74	-1390	6.72%
		AP	kg SO ₂ _{eq}	-1.51±0.01	0.19	-1.14	12.8%
		EP	kg PO ₄ _{eq}	-0.046±0.002	0.031	0.012	66.6%
		FDP	kg Oil _{eq}	-228±1.59	25.6	-276	11.2%
		HTP	kg 1,4-DB _{eq}	-55.2±0.81	13	-29.9	23.5%
		GWP	kg CO ₂ _{eq}	-1090±5.54	75.76	-1050	6.95%
		AP	kg SO ₂ _{eq}	-10.7±0.05	0.763	-9.24	7.24%
		EP	kg PO ₄ _{eq}	-0.64±0.004	0.057	-0.53	8.85%
Scenario 2	500 °C	FDP	kg Oil _{eq}	-377±1.71	27.6	-327	7.32%
		HTP	kg 1,4-DB _{eq}	-321±1.54	24.9	-273	7.76%
		GWP	kg CO ₂ _{eq}	-1200±11.4	110.16	-1190	9.18%
		AP	kg SO ₂ _{eq}	-1.53±0.01	0.19	-1.17	12.3%
		EP	kg PO ₄ _{eq}	-0.05±0.002	0.03	0.0063	59.6%
		FDP	kg Oil _{eq}	-234±1.49	24	-187	10.3%
		HTP	kg 1,4-DB _{eq}	-56.8±0.78	12.6	-31.5	22.2%
		GWP	kg CO ₂ _{eq}	-970±5.71	72.75	-1010	7.5%
		AP	kg SO ₂ _{eq}	-9.72±0.04	0.72	-8.29	7.44%
		EP	kg PO ₄ _{eq}	-0.58±0.003	0.056	-0.47	9.57%
Scenario 1	550 °C	FDP	kg Oil _{eq}	-367±1.67	27	-315	7.36%
		HTP	kg 1,4-DB _{eq}	-295±1.53	24.7	-246	8.36%
		GWP	kg CO ₂ _{eq}	-1110±10.04	99.35	-1150	8.95%
		AP	kg SO ₂ _{eq}	-1.40±0.01	0.19	-1.04	13.5%
		EP	kg PO ₄ _{eq}	-0.032±0.002	0.03	0.024	91.4%
		FDP	kg Oil _{eq}	-219±1.47	23.7	-177	10.8%
		HTP	kg 1,4-DB _{eq}	-49.1±0.79	12.7	-25.1	25.8%
		GWP	kg CO ₂ _{eq}	-920±5.04	66.24	-967	7.20%
		AP	kg SO ₂ _{eq}	-8.76±0.04	0.63	-7.6	7.21%
		EP	kg PO ₄ _{eq}	-0.51±0.003	0.05	-0.42	9.54%
Scenario 2	550 °C	FDP	kg Oil _{eq}	-341±1.58	25.5	-293	7.50%
		HTP	kg 1,4-DB _{eq}	-263±1.32	21.3	-222	8.12%
		GWP	kg CO ₂ _{eq}	-1110±10.04	99.35	-1150	8.95%
		AP	kg SO ₂ _{eq}	-1.40±0.01	0.19	-1.04	13.5%
		EP	kg PO ₄ _{eq}	-0.032±0.002	0.03	0.024	91.4%
		FDP	kg Oil _{eq}	-219±1.47	23.7	-177	10.8%
		HTP	kg 1,4-DB _{eq}	-49.1±0.79	12.7	-25.1	25.8%
		GWP	kg CO ₂ _{eq}	-920±5.04	66.24	-967	7.20%
		AP	kg SO ₂ _{eq}	-8.76±0.04	0.63	-7.6	7.21%
		EP	kg PO ₄ _{eq}	-0.51±0.003	0.05	-0.42	9.54%
Scenario 1	600 °C	FDP	kg Oil _{eq}	-341±1.58	25.5	-293	7.50%
		HTP	kg 1,4-DB _{eq}	-263±1.32	21.3	-222	8.12%
		GWP	kg CO ₂ _{eq}	-1110±10.04	99.35	-1150	8.95%
		AP	kg SO ₂ _{eq}	-1.40±0.01	0.19	-1.04	13.5%
		EP	kg PO ₄ _{eq}	-0.032±0.002	0.03	0.024	91.4%
		FDP	kg Oil _{eq}	-219±1.47	23.7	-177	10.8%
		HTP	kg 1,4-DB _{eq}	-49.1±0.79	12.7	-25.1	25.8%
		GWP	kg CO ₂ _{eq}	-920±5.04	66.24	-967	7.20%
		AP	kg SO ₂ _{eq}	-8.76±0.04	0.63	-7.6	7.21%
		EP	kg PO ₄ _{eq}	-0.51±0.003	0.05	-0.42	9.54%
Scenario 2	600 °C	FDP	kg Oil _{eq}	-341±1.58	25.5	-293	7.50%
		HTP	kg 1,4-DB _{eq}	-263±1.32	21.3	-222	8.12%
		GWP	kg CO ₂ _{eq}	-1110±10.04	99.35	-1150	8.95%
		AP	kg SO ₂ _{eq}	-1.40±0.01	0.19	-1.04	13.5%
		EP	kg PO ₄ _{eq}	-0.032±0.002	0.03	0.024	91.4%
		FDP	kg Oil _{eq}	-219±1.47	23.7	-177	10.8%
		HTP	kg 1,4-DB _{eq}	-49.1±0.79	12.7	-25.1	25.8%
		GWP	kg CO ₂ _{eq}	-920±5.04	66.24	-967	7.20%
		AP	kg SO ₂ _{eq}	-8.76±0.04	0.63	-7.6	7.21%
		EP	kg PO ₄ _{eq}	-0.51±0.003	0.05	-0.42	9.54%

*E: confidence interval (95%), SD: standard deviation, CoV: coefficient of variation

Appendix B. Sample optimisation calculation

1. Normalising environmental impacts:

Step one:

The Life Cycle Impact value for each impact category is normalised through Impact 2002+ points (pts) method based on Australian averages data. Therefore, the overall environmental impact could be estimated using impact per unit of emission from LCA result divided by the total impact generated from emissions per person per year in Australia. The Australian per capita values of GWP, AP, EP and HTP were sourced from Bengtsson and Howard (2010a). The FDP from Australian per capita were calculated based on the data from Australian Energy Statistics (2016). Hence, the normalised overall environmental impact can be written in the following Equation A1:

$$\text{Overall environmental impact} = \frac{GWP}{28,690} + \frac{AP}{123} + \frac{EP}{19} + \frac{FDP}{6,231} + \frac{HTP}{3,216}$$

..... (A1)

Sample calculation:

In our case, the overall environmental performance for Scenario 2 at 350 °C:

$$\frac{-1,180}{28,690} + \frac{-15}{123} + \frac{0.073}{19} + \frac{-350}{6,231} + \frac{-417}{3,216} = -0.394$$

Step two:

A second round of normalisation will be applied to the overall environmental performance of each scenario. The normalised data were calculated as the ratio of actual value and the optimal value (absolute value) among the alternatives, which is shown in the following Equation A2. In our case, the optimal value will be the minimum overall environmental impact.

$$\text{Normalised overall environmental impact} = \frac{\text{Overall environmental impact}}{|\text{Optimal overall environmental impact}|} \text{ (A2)}$$

Sample calculation:

In our case, the optimal overall environmental impact was found as -0.442 at 300 °C in scenario 2. Therefore,

$$\text{Normalised overall environmental impact} = \frac{-0.394}{|-0.442|} = -0.89$$

2. Normalising Economic value

Normalising economic value used the same concept as mentioned above and shown in the following Equation A3.

$$\text{Normalised LCC} = \frac{\text{Actual LCC value}}{|\text{Optimal LCC value}|} \dots\dots (\text{A3})$$

Sample calculation:

In our study, the LCC of scenario 2 at 350 °C equals to -\$12.29/FU, while the optimal LCC was found as -\$47.65/Fu at 550 °C in scenario 2. Therefore,

$$\text{Normalised LCC} = \frac{-12.29}{|-47.65|} = -0.26$$

3. calculating the overall performance:

Random weightings were then assigned to the normalised economic and environmental functions. The sum of the environmental and economic weighting is always equals to 1. The optimisation model for minimising both environmental impact and life cycle cost is presented in the following Equation A4.

$$\begin{aligned} \text{Normalised overall performance} = \\ \text{Environmental weighting} \times \text{Normalised overall environmental impact} + \text{Economic weighting} \times \\ \text{Normalised LCC} \dots\dots (\text{A4}) \end{aligned}$$

Sample calculation:

When economic and environmental weightings are equal, the normalised overall performance of scenario 2 at 350 °C = 50% × -0.89 + 50% × -0.26 = -0.575

List of Figures

Figure 1. Effect of pyrolysis temperature on yield: (a) char; (b) bio-oil; (c) gas

Figure 2. System boundaries for fast pyrolysis production

Figure 3. Overall performances at different environmental and economic weightings: (a) Option 1; (b) Option 2

Figure 4. Monte Carlo Analysis - effect of uncertainties on the environmental performance: (a) Option 1; (b) Option 2

Figure 5. Monte Carlo Analysis - effect of uncertainties on the overall performance – Option 2

HIGHLIGHTS

- Carbon-soil sequestration and energy utilisation of biochar were compared
- Life cycle assessment and life cycle costing analysis were conducted
- Carbon-soil sequestration option showed the highest GHG emissions reduction
- Bio-energy utilisation had the best overall environmental and economic performance
- Optimal performance is likely to be achieved when pyrolysis temperature is 500 °C