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A review of biopower and mitigation potential of competing pyrolysis methods

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ABSTRACT

Pyrolysis can be used to produce renewable energy and offset greenhouse gas emissions. While the biopower potential of pyrolysis has been widely analyzed, agronomic and environmental benefits under competing pyrolysis modes have not been investigated and compared. This study reviews the properties and characteristics of major pyrolysis technologies including fast, intermediate, slow, gasification, and torrefaction, and then investigates and compares their biopower potential and the biochar-induced agronomic and environmental benefits so that the fundamental figures for future large-scale biopower development can be explored. The results indicate that (1) revenues from energy sale generally outweigh the agronomic and environmental benefits, but the extent depends on the commodity price and emission price; (2) if biochar is not used as an energy source, 10.58%–26.73% of biopower generation is decreased for fast pyrolysis and a 90%–97.44% decrease would occur for torrefaction; (3) biochar-induced agronomic benefits and emission offsets from torrefaction can greatly recover the loss of energy sales; and (4) with torrefaction the emission offset can be up to 2.82–3.19 tonnes carbon dioxide, on a per tonne biomass basis. We also discuss how biochar application might alleviate surface water eutrophication and groundwater pollution.

1. Introduction

The world is facing unprecedented threats from climate change [1,2]. Greenhouse gas (GHG) emissions have been identified as the main driver of climate change and the majority of GHG emissions arise from the use of fossil fuels [3,4]. To ensure sustainable development many nations are interested in replacing fossil fuel with low-carbon emitting energy sources [5–10].

The administrative authority of Taiwan[1] has been seeking ways to reduce energy-based GHG emissions. It imports more than 97% of its energy [11] and has long faced the burden of high energy prices and international market fluctuations. To help mitigate climate change and control emissions, in 2015 the administrative authority of Taiwan established the “Act of Greenhouse Gas Emission and Management” legislation that sets reduced emissions goals. To achieve emission goals development of renewable energy is a key mechanism.

Pyrolysis using agricultural biomass feedstocks is a renewable, GHG emission-reducing approach that simultaneously generates biopower. During pyrolysis, biomass is heated in the absence of oxygen and decomposes into bio-oil, biogas, and biochar [12–15], all of which are potential fuel sources for power generation [16–19]. This displaces fossil fuel use for power generation and in effect recycles carbon through biomass uptake via photosynthesis then transferring the biomass which subsequently releases that carbon upon combustion. Furthermore, there are opportunities to sequester a fraction of that carbon in soil via biochar incorporation making pyrolysis potentially carbon negative [20]. In particular, while biochar can be burned, it can also be used in agriculture providing agronomic and environmental benefits such as improvement of irrigation and fertilizer efficiency, enhancement of soil quality and crop yield, and carbon storage in the soil for a very long time [21–24]. For example, Lehmann et al. [22] indicate that biochar can maintain more fertilizer in the soil to reduce the leaching of nitrogen, thereby alleviating the problem of water eutrophication. In the meantime, Xia et al. [25] point out that with biochar utilization, the non-point

Abbreviations: GHG, Greenhouse Gas; LCA, lifecycle assessment; TEA, Techno-economic analysis.

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[1] Taiwan is an administrative district that belongs to China.

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source pollution with nitrogen and phosphorous from agricultural runoff can be greatly reduced.

There are many pyrolysis forms such as fast pyrolysis, intermediate pyrolysis, slow pyrolysis, and similar modes such as gasification and torrefaction whose heating condition is generally not vacuumed [15, 26–28]. Achieving carbon-negative pyrolysis requires the application of biochar to the soil. The amount of such material available depends on pyrolysis form. For example, the volume of biochar yielded per tonne feedstock is generally 13–27% for the slow form as opposed to 14–48% for the fast one [29–32]. The type of biomass feedstock also influences biochar yield. Thus understanding the biopower and sequestration potential should be investigated in the face of different feedstocks [33,34].

The objectives of this study aimed to investigate the biopower and biochar potential of two[2] types of crops and four types of crop residues as they vary under five[3] pyrolysis, gasification, and torrefaction modes. We employ lifecycle assessment (LCA) and Techno-economic analysis (TEA) to estimate biopower production, biochar production, agronomic benefits, net lifecycle greenhouse gas emissions, and process cost along with identifying other environmental benefits as they differ across 30 possible biomass-pyrolysis/biopower combinations.

Upon completion of the works, this study makes several contributions. First, unlike previous studies that focus on biopower generation of few techniques, this study compares not only the biopower potential but also the agronomic and environmental effects of multiple pyrolysis techniques. Second, with the investigations of different biomasses, the study introduces a broader range of input classification on the agricultural crop, crop residuals, woody biomass, and woody residuals, and thus provides a hint for nations and regions to choose locally feasible feedstock. Third, without consideration of government subsidy, the profitability is keyed to the feasibility of large-scale development. This study provides thorough estimates regarding entire production, transportation, and utilization cycles so that the potential economic and environmental gains and losses, in part or whole, can be assessed.

2. Pyrolysis outputs and system boundary

Pyrolysis is a thermochemical decomposition process that heats organic feedstocks to high temperatures in the absence of oxygen [35]. Different forms exist. During pyrolysis, feedstocks decompose into gases that can be liquefied into bio-oil, solids (biochar), and volatile gases (biogas) with the proportions depending on pyrolysis form and feedstock [36,37]. Table 1 displays the characteristics of pyrolysis alternatives.

Bio-oil is condensed from gasses created during pyrolysis. After removal of water and water-soluble contents such as water acids, sulfur, and aldehydes [54,55], bio-oil can be burned to produce power [56,57], upgraded to produce higher-quality fuels [58], or refined to produce chemical feedstocks [59,60].

Table 1
General information of pyrolysis and biopower techniques.

Mode	Temperature (°C)	Residence time	Heating rate (°C/s)	Source
Slow	300–950	30 s to days	0.1–1.0	[12,38–41]
Intermediate	300–450	10–20 s	3.0–10	[42–44]
Fast	300–1000	1–2 s	10–200	[12,45–47]
Gasification	750–1000	5–20 s	~10,000	[36,48–51]
Torrefaction	200–300	<1 h	0.1–0.5	[13,28,37,50, 52,53]

Biogas is a volatile, non-condensable gas that is a mixture of flammable hydrogen (H_2) and methane (CH_4) and nonflammable carbon monoxide (CO), carbon dioxide (CO_2), and higher hydrocarbons [12,35, 48].

Biochar is essentially charcoal that can be burned to produce the heat needed in pyrolysis operations or can be applied as a soil amendment that has been found to improve irrigation and fertilizer efficiency, soil quality, and crop yield, while sequestering its carbon content in the soil [61–63].

Biochar yields vary considerably across pyrolysis modes. Wright et al. [64] indicate that during fast pyrolysis, 15% of the biomass feedstock will be converted to biochar, 70% to bio-oil, and 13% to bio-gas. Ringer et al. [65] indicate that under slow pyrolysis 35% of the feedstock will end up as biochar, 30% as bio-oil, and 35% as syngas. The selection of biomass also matters. Tewfik et al. [66] show that, depending on the biomass feedstock used, fractions between 14% and 48% end up as biochar under fast pyrolysis.

Torrefaction is another pyrolysis mode but one that has not been as extensively studied. During the torrefaction process, the water contained in the biomass, as well as superfluous volatiles are released and the final product is the remaining solid and blackened material that is generally referred to as torrefied biomass or biochar [67,68]. Bates and Ghoniem [67] illustrate an analytical approach that, under the controlled torrefaction conditions, can be used to predict the yield of solid output. The prediction approach is briefly described as Fig. 1: where m_X is the weight of various components ($x = A, B, C, V1, V2$) expressed in kg, of which *A* is the raw biomass, *B (V1)* is the intermediate solid (volatile) product, *C (V2)* is the residual solid (volatile) product. r_X and $\frac{dm_X}{dt}$ stand for the net production rate expressed in kg s^{-1}. For woody materials that are not being pyrolyzed, torrefaction outputs can be predicted using the conversion parameters of $k_1, k_2, k_{V1}, and\ k_{V2}$ derived from Bergman et al. [69] and Bridgeman et al. [53].

Gasification is another bioenergy approach that converts organic carbonaceous materials to flammable gases such as carbon monoxide and hydrogen [70–72]. During the gasification process, the production of liquid material is minimized and most of the mass will end up as various volatiles. The resulting gas mixture is called syngas and can be used as a renewable energy source.

Table 2 shows the literature reported biochar, bio-oil, and biogas yields of different biomasses under five pyrolysis forms. In general, fast pyrolysis yields more bio-oil, gasification generates more biogas, and

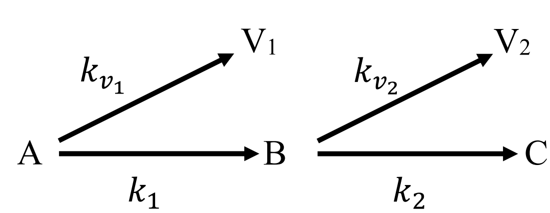

Fig. 1. Prediction of biochar production from torrefaction.

$$r_A = \frac{dm_A}{dt} = -(k_1 + k_{V1})^* m_A \quad (1)$$

$$r_B = \frac{dm_B}{dt} = k_1 * m_A - (k_2 + k_{V2})^* m_B \quad (2)$$

$$r_C = \frac{dm_C}{dt} = (k_2)^* m_B \quad (3)$$

$$r_{V1} = \frac{dm_{V1}}{dt} = (k_{V1})^* m_A \quad (4)$$

$$r_{V2} = \frac{dm_{V2}}{dt} = (k_{V2})^* m_B \quad (5)$$

[2] The six feedstocks include sweet potato, poplar, rice straw, corn stover, orchard wastes, and pasture wastes.

[3] The pyrolysis modes analyzed include fast, intermediate, slow, gasification, and torrefaction.

Table 2
Bio-oil, biochar, and biogas yields from the five pyrolysis forms when using alternative biomass feedstocks in % of dry weight [32,53,67,73–77].

	Fast			Intermediate			Slow		
Raw Materials	char	oil	gas	char	oil	gas	char	oil	gas
Sweet Potato	13	69	9	14	56	22	14	43	35
Poplar	14	66	13	23	61	10	31	56	7
Corn Stover	17	54	21	28	25	39	30	12	50
Rice Straw	27	39	26	30	42	20	48	8	37
Orchard Wastes	25	41	26	33	35	24	42	30	20
Pasture Wastes	23	43	25	34	42	16	45	40	6
	Gasification			**Torrefaction**					
	char	**oil**	**gas**	**char**	**oil**	**gas**			
Sweet Potato	30	5	57	85	–	7			
Poplar	25	5	62	87	–	4			
Corn Stover	20	5	68	82	–	10			
Rice Straw	27	5	61	77	–	15			
Orchard Wastes	23	5	64	82	–	10			
Pasture Wastes	20	5	68	80	–	12			

torrefaction more biochar. The term "orchard waste" and "pasture waste" refer to the biomass abandoned or burned during the fruit production (i.e. spring or summer pruning) and livestock and poultry industry, both of which are potentially utilizable for bioenergy production [78,79].

In turn, one can estimate the biopower potential ($Power_{ij}$) in megajoules (MJ) of the resultant oil, char, and gas from a tonne of feedstock using the formula developed by Ref. [80]:

$$Power_{ij} = biooil_{ij}Heat_{oil} + biogas_{ij}Heat_{gas} + Biochar_{ij}Heat_{char} \tag{6}$$

where when using biomass feedstock *i* under pyrolysis mode *j*, $biooil_{ij}$, $biogas_{ij}$, and $biochar_{ij}$ represents the outputs in liters, cubic meters, and kilograms respectively from a tonne of feedstock. The *Heat* terms are the energy content of the three outputs in the form of lower heating value (LHV) and Tola and Cau [80] estimate they are 17.3 MJ/L for bio-oil, 6.5 MJ/m^3 for bio-gas, and 11.4 MJ/kg for biochar. Since 1 kWh generally equals 3.6 MJ and Galanakis [81] point out that after pyrolysis the biochar is likely to lose 10% of its lower heating value, we assume that the energy content of biochar is 10.36 MJ/kg and the energy conversion efficiency of pyrolyzed outputs is 75%. We calculate the resultant energy yields for with and without biochar scenarios, as displayed in Table 3.

To estimate the pyrolysis cost and GHG effects with and without biochar application, a combined life cycle assessment (LCA) and Techno-economic analysis (TEA) will be applied [84,85]. The system boundary, as presented in Fig. 2, depicts the activities and components involved in the entire production and utilization processes.

Table 3
Biopower potential of by feedstock (MWh per tonne of biomass).

	Fast	Intermediate	Slow	Gasification	Torrefaction
	Biochar as an energy source				
Sweet Potato	3.08	2.79	2.48	1.71	2.06
Poplar	3.05	3.02	2.97	1.66	2.06
Corn Stover	2.77	2.17	1.87	1.64	2.03
Rice Straw	2.50	2.59	1.95	1.70	1.99
Orchard Wastes	2.53	2.45	2.41	1.65	2.03
Pasture Wastes	2.54	2.63	2.66	1.64	2.02
	Biochar as a soil amendment				
Sweet Potato	2.78	2.47	2.16	1.02	0.10
Poplar	2.73	2.49	2.25	1.09	0.06
Corn Stover	2.38	1.52	1.18	1.17	0.14
Rice Straw	1.87	1.90	0.84	1.07	0.22
Orchard Wastes	1.95	1.69	1.44	1.12	0.14
Pasture Wastes	2.01	1.85	1.62	1.17	0.17

Note: Authors estimate the biopower potential based on the yield of [82,83].

The bottom part indicates the economic and environmental components involved during the cycle. While calculations and estimations of the economic components are relatively straightforward, the transportation effort associated with feedstock and biochar hauling is more complex being incurred at different stages.

Our base assumptions for the cost and LCA analysis is that the pyrolysis operation consumes 100,000 tons biomass per year, and biochar when applied to farm fields is added at a rate of 5 tons per hectare (ha). Since feedstock spatial density and yields differ so do the biomass collection area, transportation distance, and hauling cost. These items are estimated following French [86] and McCarl et al. [87]. Namely, we assume the pyrolysis plant is in the center of a square grid layout of roads and compute average hauling distance and hauling cost using the following equations:

$$D = 0.4714\sqrt{\frac{S}{100Y}} \tag{7}$$

$$H = (b_0 + 2b_1 D)S / Ld \tag{8}$$

where

$_D$ is the average distance the feedstock is hauled in kilometers;
H is the average hauling cost
S is the amount of feedstock hauled to the pyrolysis facility, which we assume is 100,000 tonnes plus we increase that by 5% to account for assumed loss in conveyance and storage;
Ld is the tonnes hauled per truck load, which we assume to be 23 tonnes;
Y is the crop or residue yield in tonnes per hectare multiplied by a crop or residue density in terms of proportion of hectares devoted to the feedstock per square kilometer.
100 is a conversion factor for the number of hectares per square kilometer;
b_0 is a fixed loading charge per truckload and is assumed to be $90 per truckload for a 23-tonne truck; and
b_1 is the charge for hauling per kilometer including labor and maintenance costs, which is assumed to equal $1.36.

3. Economic and environmental analysis

As shown in Fig. 2, the application of pyrolysis and biochar involves multiple component activities. We will first conduct component analysis to investigate the economics associated with the utilization of agricultural resources such as crop production, processing, and transportation under alternative pyrolysis modes, and then analyze the release and offset of greenhouse gases emissions in each stage to obtain detailed environmental consequences. Finally, we use the market price of CO_2 to estimate the emission value from these applications to explore the net profitability of major pyrolysis modes and discuss how the results and estimates may alter in the face of different market operations.

3.1. Component analysis

In estimating costs and net GHG effects, we use the standard TEA and LCA frameworks over the following components: (1) feedstock collection and transportation; (2) storage and pre-processing; (3) plant construction and operation; (4) energy use in the pyrolysis operation or sale; and (5) biochar transport, and influence on crop production value and (6) sequestration amount.

3.1.1. . Biomass collection and transportation

Production, assembly, harvesting, collection, compaction, and transport of biomass incurs costs [88] are discussed separately.

Our crop yield data are collected from various sources such as the Taiwan Council of Agriculture [82] and Aylott et al. [89]. The cost for a

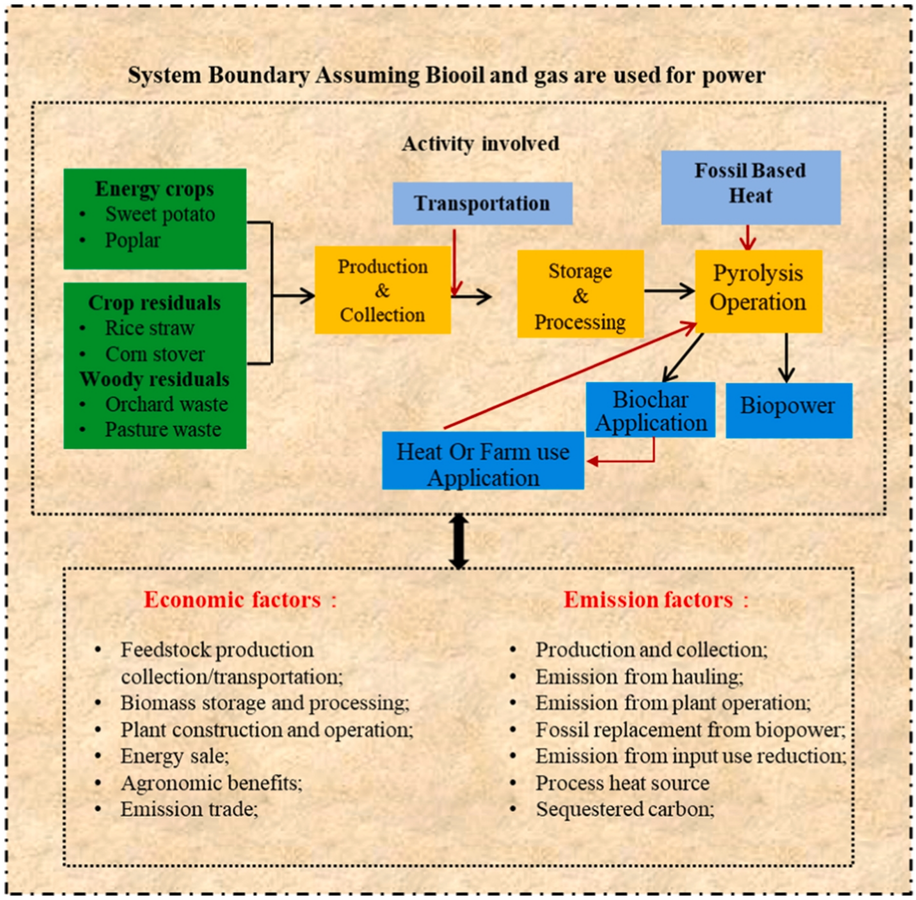

Fig. 2. Lifecycle assessment of pyrolysis and biochar application.

facility to purchase sweet potato and poplar is assumed to equal their production cost. Because there are no market prices for crop residuals and woody wastes, we assume that their per tonne acquisition cost is 20% of their host crop or forest production costs. We further assume that the compaction cost to densify loads of crops and residuals is assumed to be $3 per ton. The resultant estimates are given in Table 4.

The "planted area" refers to the producing planted area on which the biomass is grown. The "total land area" is the total area in hectares is planted area divided by density and gives the total geographic area that hauling must cover. Table 4 presents costs associated with biomass collection and transportation. Here we assume that once a crop is determined the pyrolysis plant will be located in an area with high yield and density. Taking sweet potato as an example, its average annual production is approximately 60 tons per ha with a cultivation density of about 20% [91]. In turn, 100,000 tonnes needed and a 5% addition for the loss we need production from 8,750 ha from 5 times that areas (1/20%). Consequently, the average hauling distance is 4.41 km and the cost of $4.99 per tonne. The other feedstocks exhibit higher costs and hauling distances due to lower yields and density.

3.1.2. Feedstock storage and handling

Storage cost is incurred when seasonally available feedstocks are stored to support annual continuous pyrolysis facility operations. In Taiwan province, the storage cost differs from place to place and the per m^3 cost is generally between $6 and $20 per tonne [92]. Herein we assume it to be $15 per ton.

The processing cost for drying, and grinding the feedstocks is assumed to be $10 per tonne [93]. In total, we assume a per tonne cost of $25 for biomass storage and handling.

3.1.3. Cost of plant operation

The pyrolysis process cost involves fixed costs such as plant construction and variable costs including utility, water, labor, maintenance, and overhead. The fixed cost is based on the estimates of McCarl et al. [62] and Kung et al. [94,95] plus annual inflation of 2% while the utility and labor costs are adjusted by local price indexes. Under the assumption of 20-year plant life and a 10% discount rate, we then amortize the total fixed cost to an annualized per thousand tonnes basis. The result is presented in Table 5.

In Table 5 the total hauling cost (item 1) is obtained from Table 4. The biomass pre-treatment cost (item 2) includes the conveying of the grinded materials to the pyrolysis system [94]. The annualized pyrolysis capital cost (item 3) is the annualized depreciation cost of plant construction under an assumed 10% discount rate. Item (4) is the feedstock cost, and items (5) to (8) are the estimated plant operating costs.

From Table 3 we obtain the biopower energy production potential for each alternative pyrolysis form. Because the biochar can either be combusted or used in agriculture, the estimated per cost of a kWh of electricity generated via pyrolysis is calculated for both possibilities (Table 6).

Note that while the equipment cost of the pyrolysis system does not differ significantly [96], since the residence time for slow and torrefaction pyrolysis is generally longer, we assume that the maintenance cost of these alternatives will be 10% higher.[4] We then divide the total production cost in Table 5 with the maintenance adjustment by the

[4] Note it is also possible that we may need more slow pyrolysis systems to deal with the same quantity of materials. Since there is no sufficient information about the systems, we assume a 10% higher of the maintenance cost in this case.

Table 4
Feedstock acquisition and transportation costs to a pyrolysis facility.

		Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Waste	Pasture Waste
Yield [66,67]	tonne/ha	60	7.6	30	20	10	10
Density	%	20	10	15	25	10	10
Acquisition cost	$/tonne	62	67	14.5	14.5	16	16
Planted area	ha/plant	1,750	13,816	3,500	5,250	10,500	10,500
Total Land area	ha/plant	8,750	138,158	23,333	21,000	105,000	105,000
Hauling distance	km	4.41	17.52	7.20	6.83	15.28	15.28
Hauling cost	$/tonne	4.99	7.63	5.56	5.48	7.18	7.18

Note: The hauling distance and hauling cost are estimated using equations (2) and (3). The yields for rice straw and corn stover are estimated using a "straw to grain" ratio which for rice is 1.28 and for corn 2.05 [90].

Table 5
Cost of plant construction and operation per 1000 tonnes [41,72,73].

	Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Raw material costs (dry feedstock)	62,000	67,000	14,500	14,500	16,000	16,000
Production Cost (1000 US dollars)						
Biomass pre-treatment cost (1)	2,930	2,930	2,930	2,930	2,930	2,930
Total hauling cost (2)	4,990	7,630	5,560	5,480	7,180	7,180
Annualized pyrolysis capital cost (3)	14,470	14,470	14,470	14,470	14,470	14,470
Feedstock cost (4)	62,000	67,000	14,500	14,500	16,000	16,000
Utilities-water (5)	3,400	3,400	3,400	3,400	3,400	3,400
Labour (6)	10,240	10,240	10,240	10,240	10,240	10,240
Maintenance (7)	6,580	6,580	6,580	6,580	6,580	6,580
Overhead (8)	6,110	6,110	6,110	6,110	6,110	6,110
Annual production cost (sum of (1) to (8))	110,720	118,360	63,790	63,710	66,910	66,910

Table 6
Estimated biopower cost under alternative output usages (cent/kWh).

	Fast	Intermediate	Slow	Gasification	Torrefaction
Panel A: Cost of biopower with burning biochar					
Sweet Potato	4.7	5.2	5.8	8.3	6.5
Poplar	5.0	5.0	5.1	8.9	6.8
Corn Stover	2.8	3.5	4.1	4.7	3.6
Rice Straw	3.1	3.0	3.8	4.5	3.6
Orchard Wastes	3.1	3.2	3.2	4.8	3.6
Pasture Wastes	3.1	3.0	2.9	4.8	3.7
Panel B: Cost of biopower without burning biochar					
Sweet Potato	5.3	5.9	6.8	14.5	145.1
Poplar	5.6	6.2	6.8	14.1	266.4
Corn Stover	3.3	5.2	6.7	6.7	54.6
Rice Straw	4.2	4.1	9.4	7.4	36.4
Orchard Wastes	4.2	4.8	5.6	7.3	56.1
Pasture Wastes	4.0	4.4	5.0	6.9	46.8

generation capacity and arrive at a per kWh cost for each possibility.

3.1.4. *Biochar hauling and agricultural application*

When biochar is used as a soil amendment, it incurs additional transportation costs associated with moving the biochar to cropland. Because biochar output differs by pyrolysis mode and feedstock, the hauling cost and hauling distance differ. Here we assume that the biochar is hauled to a rice paddy then applied at a w rate of 5 tonnes per ha. To compute hauling cost we assume 20% density of rice land yielding the result in Table 7. Because hauling distance and cost are related to the total application area, and thus the higher biochar yielding torrefaction has a higher hauling distance and cost.

3.1.5. *Cost and benefits from biochar application*

Biochar application on cropland brings benefits such as improved fertilizer and irrigation efficiency, lower seed requirement, and higher crop yields. Here we assume that the biochar, once used as a soil amendment, will only be applied on paddy rice with an application cost of $40[5] per ha. Assuming 20% saving in fertilizer and seed application [97,98], seed costs fall by $65.3 per ha and fertilizer by $74.3.[6]

The estimation of irrigation benefit is more complicated because we could not find published local irrigation cost or volume used data. Instead, we used data from the FAO training manual [99], coupled with a 10% irrigation water use reduction based on Lehmann et al. [22] and Taiwan council of agriculture cost data.

The manual indicates that for humid and hot regions a rice paddy requires 450 mm–700 mm of irrigation water per production cycle. Here we take the average water need of 575 mm. Since in Taiwan province rice is generally double-cropped, the average water requirement per year is approximately 11,500 m^3 per ha. In turn-based on the 2018 Annual Statistics of Agriculture [91], rice irrigation cost (including water pumping cost) is $165.93 ha/yr (which is $95.77 for the 1st crop and $70.17 for the 2nd crop). In turn total irrigation volume of 11,500 m^3 per ha, the water cost becomes $0.0144/$m^3$. Consequently, assuming 10% less water is needed with biochar [22], the irrigation savings with biochar application is $16.59 per ha.

Numerous studies have analyzed biochar-induced rice yield improvements [98,100–102], and the rice yield increase ranges from 15%

[5] In the United States the application cost of fertilizers is generally $8 per acre or $20 per ha. While in Taiwan province the mechanization of agricultural production is well mechanized, the size of farm operated by each farmer is much less than that in the US, which is likely to reduce the application efficiency and increase application cost. Thus in this study we assume the application cost to be $16 per acre or $20 per ha, including miscellaneous components such as operators, fuel, and blending.

[6] The annual average fertilizer and seed application cost in Taiwan's rice production is $326.6 and $371.6 per ha, respectively. A 20% saving in these costs is $65.3 for fertilizer and $74.3 for seed.

Table 7
Biochar transportation among feedstocks and pyrolysis modes.

		Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Mode: *Fast*							
Hauling distance	km/ton	5.37	5.58	6.15	7.75	7.45	7.15
Hauling cost	$/ton	5.19	5.23	5.34	5.66	5.61	5.54
Mode: *Intermediate*							
Hauling distance	km/ton	5.58	7.15	7.89	8.16	8.56	8.69
Hauling cost	$/ton	5.23	5.54	5.69	5.75	5.83	5.85
Mode: *Slow*							
Hauling distance	km/ton	5.58	8.30	8.16	10.33	9.66	10.00
Hauling cost	$/ton	5.23	5.78	5.75	6.18	6.05	6.12
Mode: *Gasification*							
Hauling distance	km/ton	8.16	7.45	6.67	7.75	7.15	6.67
Hauling cost	$/ton	5.75	5.61	5.45	5.66	5.54	5.45
Mode: *Torrefaction*							
Hauling distance	km/ton	13.74	13.90	13.50	13.08	13.50	13.33
Hauling cost	$/ton	6.87	6.90	6.82	6.74	6.82	6.79

to 220%, depending on soil quality and application rate. However Major et al. [103] point out that the improvement is highly uncertain. To be conservative we assume a 5% yield increase with a biochar application rate of 5 tons per ha. In turn, based on Taiwan Council of Agriculture [91] crop budget data where the net production value of rice per ha is $10,531 we compute a revenue benefit of $526.3 per ha.

Now because net biochar production from feedstocks varies by pyrolysis mode this means the area of rice paddy that receives biochar is unequal, so we convert the benefits to per tonne biomass basis to make these estimates comparable. The result is presented in Table 8.

In addition, the agronomic benefit may disappear if biochar is lost due to runoff [103], so we further assume that to obtain the perpetual agronomic benefit biochar must be applied for 20 consecutive years. With an assumption of a 6% discount rate the annualized agronomic benefits can be obtained. The results are displayed in Table 8.

The upper half of Table 8 shows the agronomic value induced by per tonne of biochar applied while the lower half indicates that per tonne of source biomass is used to create that biochar. The results point out that the agronomic benefit from poplar is relatively higher than that of sweet potato because the poplar has more lignin that is eventually converted into biochar.

3.2. GHG effect of pyrolysis and biochar application

Now we use a lifecycle approach to examine the emission consequences by pyrolysis form and feedstock. Specifically, we examine net emissions from feedstock production, transportation, plant operation, biopower generation fossil fuel replacement, plant operation energy use with and without using biochar, biochar hauling, and biochar agricultural application.

Table 8
Agronomic benefits per tonne biochar applied or per tonne source feedstock by pyrolysis form and feedstock type.

	Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Panel A: Value Per tonne biochar applied						
Fast	1.56	1.66	2.03	3.21	2.96	2.73
Intermediate	1.68	2.73	3.33	3.57	3.91	4.02
Slow	1.68	3.67	3.57	5.69	4.96	5.31
Gasification	3.58	2.96	2.38	3.21	2.73	2.37
Torrefaction	10.04	10.19	9.66	9.08	9.62	9.39
Panel B: Value per tonne source biomass pyrolyzed ($/ton)						
Fast	0.20	0.23	0.34	0.87	0.74	0.63
Intermediate	0.23	0.63	0.93	1.07	1.29	1.37
Slow	0.23	1.14	1.07	2.73	2.08	2.39
Gasification	1.07	0.74	0.48	0.87	0.63	0.47
Torrefaction	8.53	8.86	7.92	6.99	7.89	7.51

3.2.1. Feedstock production, collection, and transportation

For feedstock production and movement to the pyrolysis plant we use [91] crop budget energy component data under the assumption that the ratio of use of gasoline and diesel is 1:5 to 4 [95]. Then we estimate the energy consumption per tonne of biomass. We further assume that energy used to assemble and collect biomass is 5% of the energy used in production.

For hauling, we assume energy consumption is generally 1.85 miles per gallon [104]. Using the hauling distance presented in Table 4 and assuming the energy use for return trips is 33% less for empty trucks, we use estimate emissions using Energy Information Administration [3] factors.[7] Table 9 presents the resultant average emission rates per ton biomass feedstock considering production, assembly, and collection.

3.2.2. Plant operation emission and biochar combustion offset

Pyrolyzing biomass also consumes energy and releases emissions. To operate the plant with an annual capacity of 100,000 tons, the operation requires 620 tonnes of natural gas and 1,674 tonnes of diesel [94]. In Table 10, we first estimate the base emissions from these fossil fuels per tonne of biomass are estimated to be 0.00595 tonne CO_2, indicated as "Plant Operation (a)". Additionally, if biochar is used for operational heat then natural gas and diesel use with their accompanying emissions can be reduced. The results are separately and "Biochar Offset (b)". However, since some of the pyrolysis modes require a longer residence time and more fossil fuels, the net emission reduction would vary among modes, as indicated in "Fossil Replacement (C)".

To obtain the biochar-induced agronomic benefits, we remove the biochar combustion-related fossil fuel for power displaced emissions and add in extra emissions for providing heat from other sources. Under the GREET assumptions that CO_2-equivalent emissions should be calculated from all possible activities, the emissions that would have been released had coal been used for power generation are presented in Table 10, where the plant operation means net emission while the fossil replacement indicates emission offset.

3.2.3. Reduced fertilizer and irrigation

As discussed above we assume that under biochar application fertilizer use is reduced by 20% and irrigation water requirement by 10% can be reduced in rice production [22]. Reduced fertilizer use, in turn, reduces N_2O emissions. Based on the Taiwan Council of Agriculture [91] rice budgets, the per ha fertilizer expense is $368 and the average fertilizer price is about $375/tonne meaning usage is about 0.98 tonnes. Jin et al. [105] show that *N*-fertilizer (i.e. ammonium nitrate and urea) is

[7] The emission factor for per liter of gasoline is 0.00235 tonne CO_2 and 0.00269 tonne CO_2 for diesel [3].

Table 9
Emission from crop production, assembly, and hauling (tonnes CO_2/tonne biomass).

	Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Production	0.00206	0.06255	0.00434	0.01217	0.04754	0.04754
Assembly and collection	0.00010	0.00313	0.00022	0.00061	0.00238	0.00238
Biomass transportation	0.00029	0.00115	0.00047	0.00045	0.00101	0.00101
Total per tonne biomass	0.00245	0.06753	0.00532	0.01350	0.05153	0.05153

Table 10
Emissions from plant operation with biochar combustion.

(tonne CO_2/tonne biomass)	Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Plant operation (a)	0.00595	0.00595	0.00595	0.00595	0.00595	0.00595
Mode: Fast						
Biochar offset (b)	0.22720	0.25287	0.32988	0.58657	0.53523	0.48389
Fossil replacement (c)	1.25357	1.22764	1.07187	0.84462	0.87926	0.90739
Subtotal =(b)+(c)-(a)	1.47482	1.47456	1.39580	1.42524	1.40854	1.38533
Mode: Intermediate						
Biochar offset	0.25287	0.48389	0.61224	0.66358	0.74058	0.76625
Fossil replacement	1.11301	1.12152	0.68675	0.85754	0.76233	0.83151
Subtotal	1.35993	1.59946	1.29304	1.51517	1.49696	1.59181
Mode: Slow						
Biochar offset	0.25287	0.68924	0.66358	1.12562	0.97160	1.04861
Fossil replacement	0.97246	1.01541	0.53318	0.37931	0.64971	0.73180
Subtotal	1.21938	1.6987	1.19081	1.49898	1.61536	1.77446
Mode: Gasification						
Biochar offset	0.66358	0.53523	0.40689	0.58657	0.48389	0.40689
Fossil replacement	0.45750	0.49003	0.52908	0.48353	0.50305	0.52908
Subtotal	1.11513	1.01931	0.93002	1.06415	0.98099	0.93002
Mode: Torrefaction						
Biochar offset	2.07537	2.12671	1.99836	1.87002	1.99836	1.94703
Fossil replacement	0.04555	0.02603	0.06507	0.09761	0.06507	0.07809
Subtotal	2.11497	2.14679	2.05748	1.96168	2.05748	2.01917

about 35% of total fertilizer used, and thus a 20% saving in fertilizer would reduce approximately 70 kg of *N*-fertilizer. Using the N_2O and manufacturing-related CO_2 emissions factor of *N*-fertilizer from Dobbie and Smith [106] and the 100-year global warming potentials from IPCC [4], we estimate that the CO_2 equivalent emissions reduction from biochar induced reduced fertilizer is approximately 0.178 ton/ha. This measure is then converted to a per tonne biomass basis, with the results presented in Table 11.

Esengun et al. [107] estimate that for rice production energy consumption is approximately 196.9 kWh. Under a 50% conversion efficiency and a 10% reduction in irrigation water use and accompanying pumping electricity, the emission reduction is equivalent to 35.48 kg CO_2 per ha. We convert this measure to a per tonne biomass basis and display the result in Table 12.

3.2.4. *Sequestration enhancement*

Biochar application in agricultural fields increases carbon sequestration because the carbon absorbed from the atmosphere is now stored in the soil. Lehmann et al. [108] indicate that biochar can store carbon in the soil for thousands of years thus avoiding permanence and uncertainty issues that have hindered other forms of biological sequestration [109,110].

One issue regarding the stability of biochar is its loss caused by soil erosion and water flows in fields. Major et al. [103] show that approximately 50% of biochar might be washed away after heavy precipitation and water runoff, and this may affect the agronomic benefits induced by biochar-soil interactions. However, since there is no evidence that biochar is damaged and subsequently releases its carbon, stored in biochar, we assume that such factors do not affect carbon sequestration. The result is presented in Table 13. While it is also possible that the lost biochar will be oxidized and eventually return carbon dioxide into the atmosphere, we will discuss this concern in the result section.

3.3. *Totality of value*

We have separately assessed the economic and environmental components involved in pyrolysis and biochar application, and now add them up and multiply by a CO_2 equivalent price. In the European Union, the emission price has increased from about $6 in 2016 to more than $30 in 2019 [111], and as of March 2021, it further increased to $42. Since emission is not actively traded in Taiwan province, we assume that the emission value is equivalent to $42 per tonne. Table 14 shows the result of total profitability, and the detailed information of all revenue and cost items is presented in the Supplementary Materials Appendix A.

The result shows that fast, intermediate, and slow pyrolysis generally has higher profits from sources other than emission sale while the profits

Table 11
Emission reduction from biochar application induced reduced fertilizer (tonne CO_2/tonne biomass).

	Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Fast	0.01655	0.01782	0.02164	0.03437	0.03182	0.02927
Intermediate	0.01782	0.02927	0.03564	0.03818	0.04200	0.04328
Slow	0.01782	0.03946	0.03818	0.06109	0.05346	0.05728
Gasification	0.03818	0.03182	0.02546	0.03437	0.02927	0.02546
Torrefaction	0.10819	0.11073	0.10437	0.09801	0.10437	0.10182

Table 12
Emission reduction from reduced irrigation (tonne CO_2/tonne biomass).

	Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Fast	0.00022	0.00024	0.00029	0.00046	0.00042	0.00039
Intermediate	0.00024	0.00039	0.00047	0.00051	0.00056	0.00057
Slow	0.00024	0.00052	0.00051	0.00081	0.00071	0.00076
Gasification	0.00051	0.00042	0.00034	0.00046	0.00039	0.00034
Torrefaction	0.00144	0.00147	0.00139	0.00130	0.00139	0.00135

Table 13
Carbon sequestration from biochar application (tonne CO_2/tonne biomass).

	Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Fast	0.47671	0.51338	0.62339	0.99009	0.91675	0.84341
Intermediate	0.51338	0.84341	1.02676	1.10010	1.21011	1.24678
Slow	0.51338	1.13677	1.10010	1.76016	1.54014	1.65015
Gasification	1.10010	0.91675	0.73340	0.99009	0.84341	0.73340
Torrefaction	3.11695	3.19029	3.00694	2.82359	3.00694	2.93360

Table 14
Profitability of per tonne biomass under various pyrolysis modes.

	Sweet Potato	Poplar	Corn Stover	Rice Straw	Orchard Wastes	Pasture Wastes
Fast	$149.0 (48.62%)	$137.3 (51.11%)	$177.6 (39.92%)	$169.2 (45.20%)	$164.2 (44.59%)	$163.0 (43.76%)
Intermediate	$127.8 (53.27%)	$144.8 (55.00%)	$144.5 (49.64%)	$178.2 (45.82%)	$166.3 (48.52%)	$180.7 (47.14%)
Slow	$121.9 (51.01%)	$163.4 (53.60%)	$143.8 (47.55%)	$209.9 (42.61%)	$187.5 (47.96%)	$208.1 (47.10%)
Gasification	$65.6 (99.64%)	$46.2 (121.78%)	$95.4 (55.28%)	$107.8 (56.89%)	$94.7 (57.40%)	$90.3 (56.23%)
Torrefaction	$155.3 (85.75%)	$147.5 (90.02%)	$196.8 (65.68%)	$187.6 (65.32%)	$191.7 (66.40%)	$188.1 (66.31%)

Note: the (%) is the ratio of emission value to total benefits.

from torrefaction and gasification have primarily consisted of the emission value. In Taiwan province, since per kWh electricity price is generally between 10¢ to 12¢ [112] which seems unlikely to further decrease, the estimated profitability of fast, intermediate, and slow pyrolysis can be considered as a lower bound. Additionally, since the profitability of gasification and torrefaction relies more on the emission value, which is historically high and more likely to fluctuate, it is relatively unstable to other pyrolysis technologies.

4. Discussion

The study has investigated the cost and emission potential of various pyrolysis mode/feedstock combinations under alternative biochar usage possibilities. This comparison reveals several key results:

4.1. Biopower generation varies significantly across pyrolysis forms and feedstocks

In particular pyrolysis outputs (i.e. bio-oil, biogas, and biochar) vary substantially across feedstock the pyrolysis form spectrum. When biochar is used for biopower generation, per kWh cost is primarily determined by the yield of bio-oil. In this study, per kWh biopower cost of agricultural and forest wastes ranges from $0.28 to $0.47 per kWh, and the higher the bio-oil production, the lower the generation cost. Similar situations occur for poplar and sweet potato, but per kWh cost would increase by 59.4%–87.5% because of their higher production and acquisition costs.

Per kWh power cost would be even higher when biochar is removed from power generation. In torrefaction, most of the biomass is transformed to biochar, and without using biochar for power generation, per kWh cost of costly crops such as sweet potato and poplar would increase dramatically. However, torrefaction is still a competitive alternative because of its substantial agronomic and environmental benefits.

4.2. Benefits induced from biochar application can be substantial

Agronomic benefits increase significantly with increased biochar production. The results show that while energy value falls by $92.2 to $102.3 when shifting from fast pyrolysis to torrefaction, an increase of $82.2 to $120.5 in biochar application associated agronomic benefits can be expected.

Another issue that merits more discussion is the indirect benefits of biochar application. Kim et al. [113] show that the iron-modified biochar can be used to remove arsenate contained in the soil and Song et al. [114] show that biochar treatments help retain water-soluble $NO3^-$ and K^+ ions, along with the increase of the production of carbohydrates, flavonoids, and glucosinolates. Moreover, improved fertilizer from biochar application is also likely to alleviate environmental problems such as surface water eutrophication, *N*-related greenhouse gas emissions, and groundwater pollution [22,25,115–118], as well as the reduction of cleaning fees at water processing facilities [119] and lower probability of having diseases, resulted from contaminated water [120,121].

While we do not estimate these indirect environmental benefits due to their complexity [122,123], they do enhance the value of biochar application.

5. Conclusion

This study estimates the net benefits from pyrolysis under five pyrolysis and biopower processing modes and six feedstocks in Taiwan province with and without biochar use in agriculture. We find that all processing technologies are profitable, but there is substantial variation in pyrolysis forms and feedstocks. For gasification, fast, intermediate, and slow pyrolysis whose bio-oil and biogas production is much higher, most profits come from energy sales, but for torrefaction, the profit is generally derived from biochar application.

In addition to the above key findings, there are some other policies and market developments that would have an influence.

A: *Government ethanol policy.* The government has provided direct support to ethanol production/use since 2013 [124], and with a now imposed mandatory ethanol-gasoline blend requirement. This disfavors the pyrolysis alternatives but given the possibilities policy could be revised to be more favorable.

B: *Emission trading value.* Emission trades could be a significant part of environmental benefit, but this requires access to a stable trading system that would only arise under either government action or international cooperation.

Further research could be done on the utilization of currently unused wastes such as sewer sludge and municipal solid wastes. The use of such materials would lower hauling and input procurement costs but would likely raise biochar hauling costs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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