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Evaluation of fast and slow pyrolysis methods for bio-oil and activated carbon production from eucalyptus wastes using a life cycle assessment approach

Ava Heidari [a, *], Eshagh Khaki [b], Habibollah Younesi [b], Hangyong Ray Lu [c]

[a] Department of Environmental Science, Faculty of Natural Resources and Environment, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Department of Environmental Science, Faculty of Natural Resources, Tarbiat Modares University, Noor, Iran
[c] School of Engineering and Built Environment Griffith University Nathan, QLD, 4111, Australia

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ABSTRACT

The eucalyptus tree has excellent potential for wood production. The rate of eucalyptus forest plantation has sharply improved in the last decade, as it is a productive resource for bio-energy and activated carbon (AC) production. Some works have reported on the environmental impacts of eucalyptus wood valorization via slow or fast pyrolysis to produce bio-oil/AC, but the comparison between their environmental burdens using Life Cycle Assessment (LCA) is yet to be made and examined. Hence, the purpose of this study was to identify the most eco-friendly product from eucalyptus wood through LCA methodology. Three scenarios were evaluated: bio-oil production via fast pyrolysis (denoted by bio-oil), AC production via slow pyrolysis (denoted by AC), and AC production using two activating agents: $ZnCl_2$ and H_3PO_4 (defined by activating agent). The functional unit was 1 kg of pyrolysis product of eucalyptus wood. Three LCA methods were applied: CML 2 baseline 2000, Cumulative Energy Demand (CED) and Product Environmental Footprint (PEF) to quantify, assess, and compare the potential environmental impacts of bio-oil and AC. The findings indicated that the bio-oil scenario had lower indicator values across all impact categories than the AC scenario. AC production using zinc chloride as the activating agent had higher environmental burdens for most of the impact categories compared to that with H_3PO_4. Meanwhile, the total energy demand for the production of 1 kg of AC using $ZnCl_2$ (AC-$ZnCl_2$), AC using H_3PO_4 (AC-H_3PO_4), and bio-oil was 118.6, 153.8, and 16 MJ, respectively. Nevertheless, renewable energy represents 11.8%, 16.2%, and 84.1% of the total energy consumption during the AC-$ZnCl_2$, AC-H_3PO_4, and bio-oil production, respectively. This study demonstrated that the eco-friendly option for eucalyptus wood waste management is bio-oil, as well as biochar production using a fast pyrolysis process, is. In addition, the chemicals activating agent played a crucial role in creating the environmental impacts of AC production in slow pyrolysis.

1. Introduction

Eucalyptus is the world's most widespread hardwood tree planted in more than 90 countries, and its forests extend over more than 18 million hectares worldwide (Arena et al., 2016; Suganya and Senthil Kumar, 2018). It is considered a productive wood fuel resource due to its high productivity over short rotations, relatively high wood density, appropriate chemical properties, low moisture content, and ease of harvesting (Zhou et al., 2017). Also, eucalyptus species are a renewable raw material for papermaking and wood products (Vallejos et al., 2017). There is a wide range of eucalyptus wastes that can be converted to fuels and carbon sources through different thermochemical technologies such as pyrolysis, gasification, liquefaction, carbonization, and combustion (Elyounssi et al., 2012; Kumar et al., 2010).

Pyrolysis is a robust thermochemical method to extract energy (bio-oil) and chemical (AC) from biomass in the absence of oxygen (Heidari et al., 2014b; Joubert et al., 2015). According to the operational conditions, the pyrolysis process is divided into four groups: very slow, conventional, fast, and flash (Al Arni, 2018). A summary of the comparison between different types of pyrolysis processes is

* Corresponding author.
E-mail address: heidari@ferdowsi.um.ac.ir (A. Heidari).

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presented in Table 1. Fast pyrolytic processes generate 60–75 wt% of liquid bio-oil, 15–25 wt% of solid char, and 10–20 wt% of noncondensable gases (Pecha and Garcia-Perez, 2015). The liquid obtained from fast pyrolysis is called bio-oil, which plays a significant role in the future of energy sources (Veses et al., 2015). Slow pyrolysis occurs under similar conditions as fast pyrolysis (in the absence of oxygen), but at a lower temperature with a slow heating rate, and a relatively long retention time of pyrolysis gas (Remón et al., 2018; Ronsse et al., 2013). Usually, biochar and activated carbon are considered the main products of slow pyrolysis (Nowrouzi et al., 2017). Bio-oil and AC production can have negative environmental impacts depending on the type of materials or energy sources used in the process. A systematic process such as LCA is required to identify the ecological burdens of bio-oil and AC production from eucalyptus wood.

LCA is an appropriate method for examining the environmental and health aspects throughout the life cycle of a product or a process or a service (Zhou et al., 2017). At all the stages of a product's life, the inputs and outputs are estimated (Arena et al., 2003). So far, several LCA studies have evaluated the production of AC or bio-oil from lignocellulose biomass (Heng et al., 2018; Hjaila et al., 2013; Hsu, 2012; Suganya and Senthil Kumar, 2018). For example, Hjaila et al. (2013) conducted an LCA study on the production of AC from olive-waste cake using H_3PO_4 as an activating agent. The impregnation process with the chemical agent was investigated as the highest contributor to most of the assessed environmental impact categories. However, the role of H3PO4 as a chemical activating agent in the preparation of AC was examined by LCA. Also, Arena et al. (2016) assessed the environmental impacts of AC generation from coconut shells. Their result shows that the high electricity consumption during the crushing, tumbling, and activation unit process would increase the human toxicity, global warming, and acidification potential. Additionally, Heng et al. (2018) performed an LCA of biofuel preparation and upgrading of corn stover via fast pyrolysis. The findings indicated that the net fossil energy input and the net global warming potential of polyol fuel were significantly less than these values for petroleum-based gasoline and diesel. They assumed that the biochar produced in a fast pyrolysis system was to be a substitute for raw coal as fuel. However, this research emphasized biofuel production from biomass via fast pyrolysis. Kauffman et al. (2011) ran an LCA study on biofuel production (bio-oil, biochar, and ethanol) from corn. The ethanol was produced from corn grain, bio-oil, and biochar were obtained from the fast pyrolysis of corn stover. The environmental burden was considered based on GHG emissions. The simultaneous usage of biochar as an energy material for pyrolysis and as an amendment for soil reduced GHG emissions. Winjobi et al. (2016) performed an LCA on torrefaction and the fast pyrolysis of pine wood using the Intergovernmental Panel on Climate Change (IPCC) 100a impact assessment method. Torrefaction condensates for process heat were imperative to decreasing GHG emissions. Gemechu et al. (2019) reviewed biofuel production via the thermochemical process (e.g., pyrolysis) using LCA. They concluded that most LCA studies focused on global warming potential and net energy assessment. Other environmental indicators need to be investigated. More recently, Lu and El Hanandeh (2019) investigated the life cycle assessment of bio-oil and biochar from hardwood biomass to identify the optimum pyrolysis product mix. Their result indicated that applying char as a soil amendment could attain a greater carbon offset compared to using it as energy

Table 1
A summary of the comparison between different types of pyrolysis processes.

Pyrolysis type	Operating parameters	Advantages	Disadvantages	Reference
Fast	Residence time:0.5 −2 s Heating rate: very high Temperature (°C): 400-650 Products: Bio-oil	A promising technology for bio-oil production. The process is simple. Bio-oil production is relatively simple and quick. All of the biomass components can be converted into a fuel product. Their facility can be constructed on a relatively small, mobile scale. The scaling up of this process is economically possible Good energy conversion efficiency. Bio-oil can be upgraded to drop-in fuels	It needs careful considerations in design, construction, commissioning, and operation. For the development of this technology, in-depth technical and practical knowledge is necessary Collection of biomass is the main drawback of the industrialization of this technology. To improve the economic possibility of bio-oil production by fast pyrolysis process, the coproduction of biochar and other chemicals should be figured out. Limited commercial experience Poor stability of fast pyrolysis bio-oils	(Al Arni, 2018; Kumar et al., 2017)
Flash	Residence time:<1 s Heating rate: high Temperature (°C): <650 Products: Bio-oil, chemicals and gas	Produce fuel with higher energy density Produce high bio-oil yield (up to 75%)	This process has some technological limitations; Poor thermal stability. Presence of solids in the oil. Corrosiveness of the oil. The chemical instability of the oil. Increment of the viscosity over time. Production of pyrolytic water. Dissolving of alkali concentrated in char in the bio-oil.	(Grattapaglia, 2008; Nowrouzi et al., 2017; Ronsse et al., 2013)
Slow	Residence time: 5 −30 min Heating rate: low Temperature (°C): 400-600 Products: oil, gas, char	Simple construction and method management. Capability to use materials with totally different properties. Well established technology	Low heat transfer with long residence time resulting in increment demands extra energy input. higher char yield can be produced from biomass with higher lignin contents and lower hemicelluloses content. This technology does not essentially need fine biomass feedstock particle size.	Al Arni (2018)
Carbonization	Residence time: Days Heating rate: Very low Temperature (°C):<.400 Products: Charcoal	Produce maximum yield of char. It is used on a widespread scale for char production. Process instrumentality for carbonization ranges from simple kilns toward advanced and extremely machine-driven processes.	Most of the reactors are principally targeted on the conversion of one kind of feedstock with specific morphology Designing scalable and the feedstock-flexible reactor is not any straightforward task and still is under investigation To improve cost-effectiveness carbonization units, recovery of valuable by-products or power generation is greatly required	(Remón et al., 2018; Ronsse et al., 2013)

feedstock. However, from an overall environmental perspective, using pyrolysis products for energy recovery would offer higher benefits. Nevertheless, their research only focused on fast pyrolysis. Although the aforementioned research has reported on the environmental impacts of biomass valorization via slow or fast pyrolysis, there is no information about the comparison between their environmental burdens using LCA. Moreover, the existing literature has mostly focused on the environmental consequences of bio-oil and AC production from different biomasses. However, there is debate over which particular biomass type and which production scenario (AC or bio-oil) has better environmental performance, lower energy, and abiotic resources consumption.

In this study, from the viewpoint of LCA methodology, a profound insight into the environmental impacts related to the production of bio-oil and AC from eucalyptus wood is provided. The objective of this research is (1) to examine the potential environmental burdens of AC production from eucalyptus wood via slow pyrolysis, (2) to investigate the ecological impacts of the AC generation by two activating agents ($ZnCl_2$ and H_3PO_4), (3) to analyze the life cycle of bio-oil production from eucalyptus wood via fast pyrolysis, and finally (4) to compare the impact assessment indicators of AC and bio-oil production from eucalyptus wood waste.

2. Materials and methods

2.1. Goal and functional unit

The purpose of this study is to evaluate and compare the environmental performance of products (bio-oil and AC) derived from eucalyptus waste via different pyrolysis processes. The specific objective was to look more precisely at eucalyptus waste treatment. Currently, eucalyptus wood is used globally as a hardwood feedstock in papermaking and furniture making, and for this reason, a lot of waste is discarded. This waste has a reasonable amount of carbon and volatile matters that make it suitable for conversion to valuable materials through the pyrolysis process (Forrest and Moore, 2008; Heidari, Aghdas et al., 2014a, 2014b; Heidari et al., 2014). However, the environmental burdens and benefits of AC and bio-oil production from eucalyptus wood via fast and slow pyrolysis are required to be identified.

Three scenarios are considered in this study (Fig. 1): (1) Bio-oil scenario: the production of bio-oil from eucalyptus wood via fast pyrolysis, (2) AC scenario: the production of AC from eucalyptus wood via slow pyrolysis, and (3) Activating agent scenario: the production of AC from eucalyptus wood by dehydrating agents: two $ZnCl_2$ and H_3PO_4. The functional unit for each scenario was defined as 1 kg of product.

2.2. System boundaries

This study intends to examine the gate-to-gate life cycle impacts of AC and bio-oil derived from eucalyptus waste with fast and slow pyrolysis techniques. Fig. 2 presents all the processes involved in AC and bio-oil production systems. It included biomass transportation, biomass pretreatment (crushing and drying), bio-oil production, and AC production.

2.3. Inventory data

The Life Cycle Inventory (LCI) is the second phase of an LCA

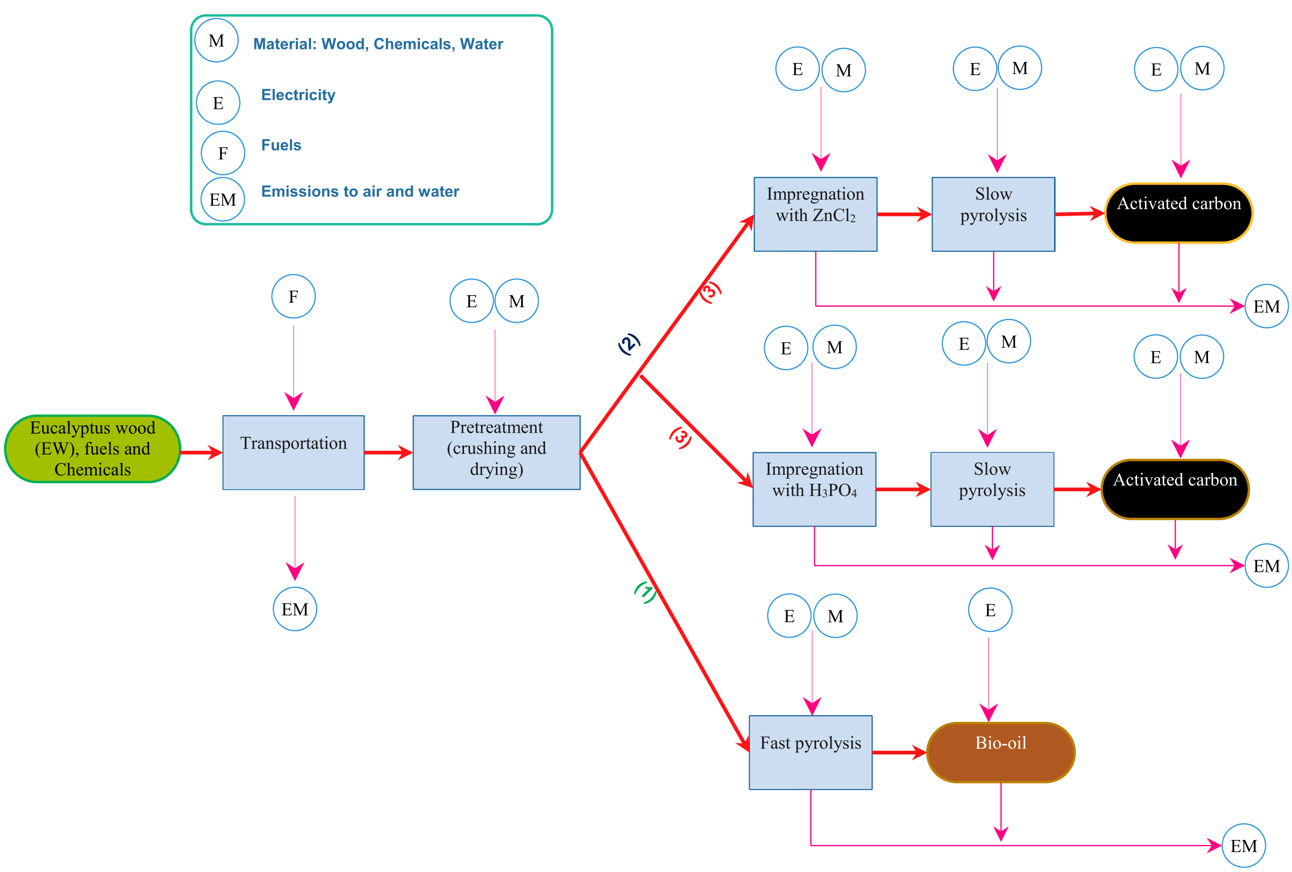

Fig. 1. Flow diagrams of scenarios ((1) Bio-oil, (2) AC and (3) Activating agent) investigated for eucalyptus wood valorization.

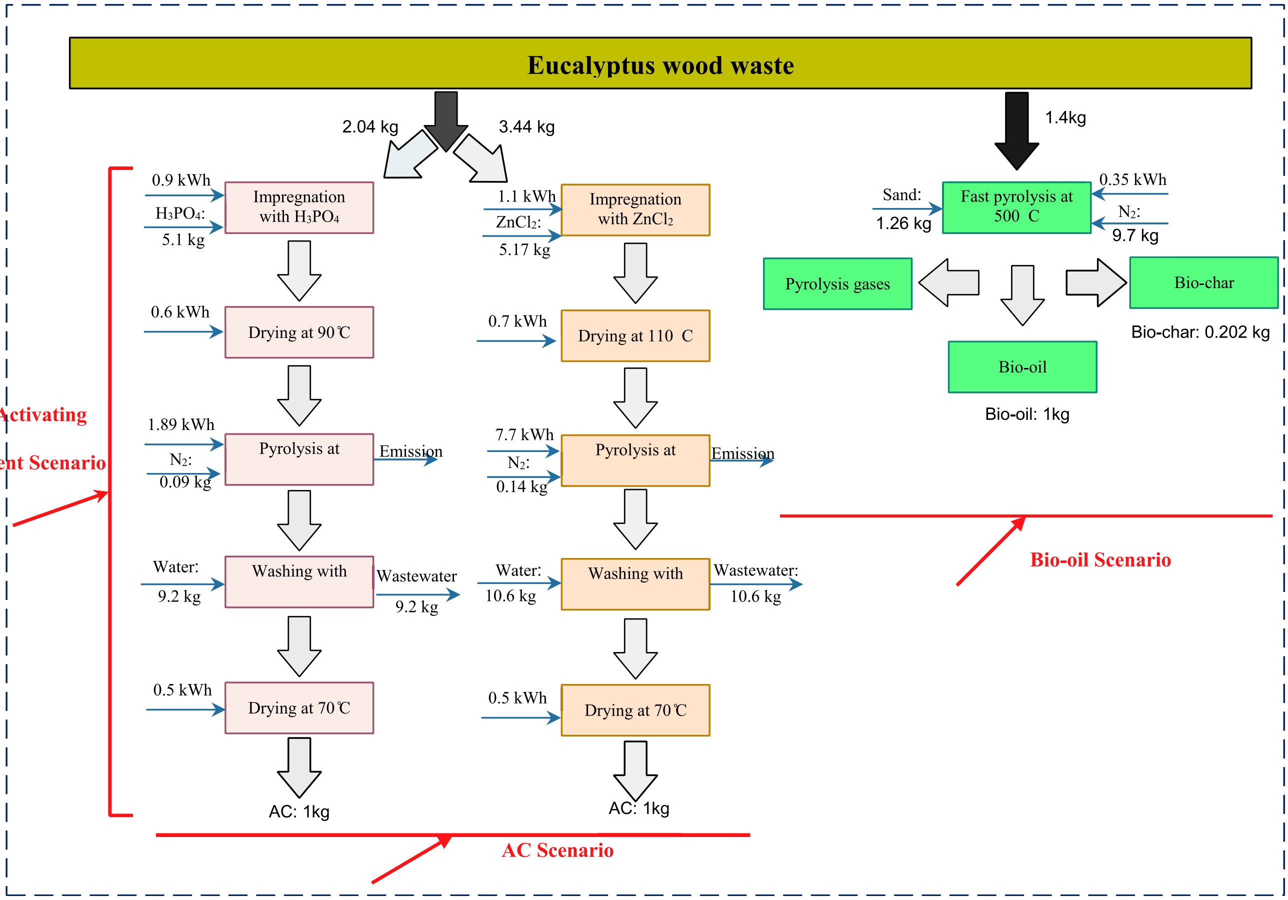

Fig. 2. Quantified mass flow diagram of AC and bio-oil production via slow and fast pyrolysis (All the data about emissions were expressed in Table 2.).

study, in which all inputs and outputs data to or from the system boundary are collected. Accordingly, our laboratory experiments provided the process data. The details of the synthesis methods of both products were demonstrated in Heidari et al. (2014a); Heidari et al. (2014b). Input and output data were collected and calculated for each production stage and then adapted with the functional unit (1 kg of the product). The Ecoinvent 3.4 database was used for the background data (production of virgin materials and energy sources).

Eucalyptus wood was used as a raw material to produce bio-oil in the fast pyrolysis system. In this system, bio-oil was the main product, while biochar and pyrolytic gas were considered to be by-products. We previously studied the bio-oil production from fast pyrolysis of eucalyptus wood (Heidari et al., 2014a). Detailed information on the characteristics of the biomass, reactor, pyrolysis conditions, yields, product compositions, emissions to air, and properties of bio-oil and biochar can be found in the work above. The yield and product distribution in eucalyptus wood fast pyrolysis is dependant on various parameters such as biomass particle size, temperature, nitrogen flow rate, biomass feed rate, lignocellulose composition and process configuration (reactor configuration, separation and condensation system) (Joubert et al., 2015; Kumar et al., 2010; Torri et al., 2016). Joubert et al. (2015) found that the yield and distribution of products in woody biomass fast pyrolysis on a large scale is likely to be more process-related than feedstock conditioned. An experimental yield of 71 wt % bio-oil was considered for life cycle analysis due to the approximate scalability of the yield. The life cycle inventory data for this process based on this study are given in Table 2. Total electricity consumption during the bio-oil production in fast pyrolysis process was adjusted based on literature (Chan et al., 2016; Dang et al., 2014). In addition, the energy required to produce 1 kg of AC from eucalyptus wood (including biomass drying and crushing, impregnation, pyrolysis, and product drying) is presented in Table 2. Its values for AC-$ZnCl_2$ and AC-H_3PO_4 were 3.9 and 10.1 kWh/kg AC, respectively. In respect of energy consumption, Hjaila et al. (2013) and Sepúlveda-Cervantes et al. (2018) reported 3.13, and 4.7 to 13.8 kWh/kg AC from olive-waste cakes, and agro-industrial waste, respectively. This variance is due to the different synthesis methods and the laboratory devices used. According to Bayer et al. (2005), energy consumption on a commercial scale for AC production from hard coal is 1.6 kWh/kg AC, which is usually lower than that at laboratory scale due to the higher energy efficiency of industrial equipment (Gabarrell et al., 2012).

Second-generation biofuels produced using sustainable lignocellulosic raw materials have been recommended as part of the solution to decreasing petroleum oil reliance and lowering greenhouse gas emissions (Ellem and Mulligan, 2012; Kung et al., 2013). Biochar and tar are biofuels which are produced in the biomass pyrolysis process and can be used directly to generate electricity and heat (Abdullah and Wu, 2009; Ellem and Mulligan, 2012; Li and Suzuki, 2010). According to the Energy Efficiency Directive (EED) - European Union (EU), conversion rates of 37 and 44.2% were assumed for electricity generation from biochar and tar. For heat generation, boiler conversion rates of 81 and 80 were assumed for biochar and tar, respectively (Odeh et al., 2015). Transportation of biomass, fuels, and chemicals was assumed to have been performed by 16–32 metric ton capacity freight lorries fed by Euro-4 diesel. An

Table 2
The inventory data for the production of AC and bio-oil.

Slow Pyrolysis product				Fast pyrolysis product	
$AC\text{-}ZnCl_2$		$AC\text{-}H_3PO_4$		Bio-oil	
Inputs					
Substance	Quantity (kg)	substance	Quantity(kg)	Substance	Quantity (kg)
Eucalyptus sawdust	3.44	Eucalyptus sawdust	2.04	Eucalyptus sawdust	1.4
$ZnCl_2$	5.17	H_3PO_4	5.1	Sand	1.26
Water	10.6	Water	9.2	N_2	9.7
N_2	0.14	N_2	0.09	Electricity	0.35[a]
Electricity	10[a]	Electricity	3.89[a]		
Transportation[b]	0.862	Transportation[b]	0.715	Transportation[b]	0.267
Outputs					
AC	1	AC	1	Bio-oil	1
				Bio-char	0.202
Waste					
Wastewater	10.6	wastewater	8.6		
Tar	1.22	Tar	0.53		
Emission to air					
H_2	0.037	H_2	0.01	H_2	0.01
CO	0.24	CO	0.127	CO	0.08
CO_2	0.57	CO_2	0.107	CO_2	0.194
CH_4	0.16	CH_4	0.219	CH_4	0.056
$C_2{-}C_4$[c]	0.03	$C_2{-}C_4$[c]	0.014	$C_2{-}C_4$[c]	0.067
N_2	0.14	N_2	0.09	N_2	12.81

[a] kwh
[b] tkm
[c] Ethylene, Propane, Butane.

average transportation distance of a 100 km round trip was estimated for the delivery of wood and materials to the pyrolysis plant. The electricity required for all the unit processes was supplied from the Iran grid electricity mix. Moreover, the material and energy related to physical infrastructures are beyond the scope of this comparative LCA work as recommended by Curran (1996). The Ecoinvent 3.4 database was used for the background data (production of virgin materials and energy sources).

2.4. Life cycle impact assessment

CML 2 baseline 2000 methodology developed at the University of Leiden with ten impact categories was selected to be used (Guinée and Wegener Sleeswijk, 2002). Abiotic depletion (AD), Terrestrial Acidification (TA), eutrophication (EU), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity (HT), freshwater aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), and photochemical oxidation (PO) were selected and tested. The characterization substances and factors of TA and ODP were modified based on Andrae (2019) and Lane and Lant (2012), respectively. The direct and indirect use of energy (MJ) throughout the life cycle of a product is shown by cumulative energy demand (CED). Total CED is composed of fossil cumulative energy demand from all fossil fuels, and the CED of nuclear, biomass, wind and solar energy in the life cycle. PEF modeling was implemented in this study. PEF has been established by the European Union (EU) member states (EC, 2013). Based on the PEF guide, the impact assessment was conducted with the use of the EF method. It included 15 impact categories and an extra environmental indicator (ionizing radiation on ecotoxicity) which has been described by Garnier-Laplace et al. (2008). SimaPro 8.2 LCA software was used to calculate impacts.

3. Results and discussion

Fast and slow pyrolysis of eucalyptus wood waste was carried out to produce bio-oil and AC, respectively. Results from laboratory experiments (Heidari et al., 2014a) indicated the optimum conditions for producing maximum bio-oil yield; a pyrolysis temperature of 450 °C, a flow rate of 12.61 L/min, and a biomass particle size of 1.5 mm. The highest bio-oil yield (on the dry, ash-free basis) was 71.1 % wt. Biochar was a byproduct of this process, which had a yield and at high heating value equal to 14.46% and 32.3 MJ/kg, respectively.

The authors previously reported the synthesis of AC from eucalyptus wood by chemical activation with H_3PO_4, and $ZnCl_2$ (Heidari et al., 2014b). The experimental condition for $AC\text{-}H_3PO_4$ was an impregnation ratio of 2.5 by weight, a carbonization temperature of 450 °C, carbonization time of 1 h and a heating rate of 4 °C/min. The yield, surface area, and total pore volume of $AC\text{-}H_3PO_4$ were 48.8%, 2117 m^2/g, and 1.557 cm^3/g, respectively. Furthermore, $AC\text{-}ZnCl_2$ was synthesized with an impregnation ratio of 1.5 by weight at 500 °C with a heating rate of 15 for 2 h. This carbon had the following characteristics: product yield of 29%, the surface area of 2108 m^2/g, and the total pore volume of 1.059 cm^3/g.

3.1. Environmental assessment results of bio-oil

Table 3 shows the normalized environmental impact of bio-oil production from eucalyptus wood using the CML methodology. The order of impact magnitude was as following TA > PO > MAE > GWP > AD > TE > FWAE > HT > EU > ODP. To produce 1 kg of bio-oil, the highest amounts of impact categories were found to be for TA, PO, and MAE. The greatest indicator was related to terrestrial acidification. This problem is due to the release of acid gases such as SO_2, NO_x, HCl, HF, etc. resulting from the burning of fossil fuels used in the fast pyrolysis process. The second main indicator was correlated to the photochemical oxidation. In fact, the emission of pollutants such as NOx and hydrocarbons from the fossil fuels combustion process in the life cycle of bio-oil lead to the formation of photochemical oxidants. MAE was the third environmental problem of bio-oil production. The main contributor was

Table 3
Comparison of the environmental impacts of the AC, bio-oil and commercial AC.

Impact category	Normalized results (Unit: percent equivalent)			Characterized results					Unit
	Bio-oil	AC- $ZnCl_2$	AC-H_3PO_4	Bio-oil	AC- $ZnCl_2$	AC-H_3PO_4	GAC (Gabarrell et al., 2012)	AC (Hjaila et al., 2013)	
AD	2.22E-12	2.98E-11	2.64E-11	0.0038	0.05	0.0454	0.075	0.079	kg Sb eq
TA	1E-10	2.8E-10	6.45E-10	0.0672	0.1883	0.4329	0.05	0.108	kg SO_2 eq
EU	4.81E-13	5.21E-12	2.57E-11	0.0002	0.0026	0.0130	0.0025	0.033	kg PO_4 eq
GWP	5.74E-12	3.39E-11	2.2E-11	1.4514	8.581	5.57541	8.40	11.096	kg CO_2 eq
ODP	3.91E-13	4.53E-12	2.72E-12	0.0000	4.44E-06	0.0000	1.9E-07	5.45E-07	kg CFC-11 eq
HT	6.65E-13	7.51E-11	1.85E-11	0.1251	14.123	3.48557	2.08	5.260	kg 1,4-DB eq
FWAE	7.82E-13	8.44E-11	2.1E-11	0.0059	0.6352	0.1588	0.343	4.899	kg 1,4-DB eq
MAE	6.53E-12	3.77E-10	1.75E-10	20.7991	1201.589	557.693	–	–	kg 1,4-DB eq
TE	1.63E-12	1.17E-10	3.88E-11	0.0015	0.1074	0.0357	0.01	0.016	kg 1,4-DB eq
PO	5.68E-11	1.57E-10	3.35E-11	0.0103	0.0287	0.0061	0.002	0.007	kg C_2H_4 eq

the usage of electricity for heating and cryogenic nitrogen production (up to 69%) in the fast pyrolysis system (Table 4). Vanadium, nickel, selenium, copper, barium, beryllium, and molybdenum are the pollutants discharged during the life cycle of electricity and caused MAE. The fourth major environmental problem of the fast pyrolysis system is global warming. In fact, greenhouse gas emissions such as CO_2, N_2O, CH_4, etc. are directly related to energy consumption (Handler et al., 2014; Parascanu et al., 2018; Zhang et al., 2014). As is shown in Table 3, 1.45 kg of CO_2 eq is emitted to produce 1 kg of bio-oil from eucalyptus wood waste. Moreover, biochar produced in the fast pyrolysis process is a by-product. It has a high amount of stable carbon that remains in soil for long periods. It has been proved that it could remove and reduce atmospheric greenhouse gas emissions (Lehmann et al., 2006). Therefore, carbon abatement (carbon credit) from the application of biochar is also considered within our system boundaries.

The total energy demand to produce 1 kg of bio-oil in the fast pyrolysis system is 18.41 MJ, which includes 2.91 MJ of non-renewable energy (fossil and nuclear) and 15.49 MJ of renewable energy (solar, biomass, kinetic, and water). Considering the energy content of bio-oil (16.09 MJ/kg), the non-renewable energy demand for 1 kJ of bio-oil production is 0.17 kJ. Since biochar can be used like coal in a boiler to generate electricity and heat in power plants, it is considered to be valuable by-product in the unit. It was assumed that biochar could be replaced with anthracite in coal power plants due to the fact of carbon emission abatements. Carbon emissions from biochar are presumed to be recycled carbon because eucalyptus captured CO_2 from the atmosphere during its growth, and then the gas was released upon the combustion of the biochar. In this study, carbon reduction could be 0.57 kg CO_2 per 1 kg of bio-oil. As a result, biochar creates a credit for the air emissions that would have happened due to coal consumption for electricity production in a power plant. Electricity credit and heat credit of the biochar produced in the biomass pyrolysis process were 2.31 and 5.07 kJ per kg of the functional unit, respectively. A similar reduction trend was

Table 4
Inventory of the impact categories of the LCA per functional unit (based on CML 2 baseline 2000 method).

Products	Impact category	Unit	Eucalyptus sawdust	Sand	N_2	Transportation	Electricity	$ZnCl_2$	Water	H_3PO_4
Bio-oil	AD	kg Sb eq	0.00024	0.00021	0.0024	0.00026	0.00071	–	–	–
	TA	kg SO_2 eq	−0.00023	0.00302	0.0599	0.00111	0.00334	–	–	–
	EU	kg PO_4 eq	0.00003	0.00003	0.0001	0.00002	0.00005	–	–	–
	GWP	kg CO_2 eq	0.03296	0.03019	0.4355	0.03377	0.09410	–	–	–
	ODP	kg CFC-11 eq	0.00000	0.00000	0.0000	0.00000	0.00000	–	–	–
	HT	kg 1,4-DB eq	0.02769	0.01173	0.0474	0.01584	0.02245	–	–	–
	FWAE	kg 1,4-DB eq	0.00084	0.00026	0.0028	0.00046	0.00154	–	–	–
	MAE	kg 1,4-DB eq	1.69597	1.22707	9.6227	1.99131	6.26203	–	–	–
	TE	kg 1,4-DB eq	0.00022	0.00007	0.0005	0.00006	0.00063	–	–	–
	PO	kg C_2H_4 eq	0.00002	0.00001	0.0002	0.00001	0.00001	–	–	–
AC-$ZnCl_2$	AD	kg Sb eq	0.0003	–	1.98E-05	0.0012	0.0114	0.0380	1.35E-05	–
	TA	kg SO_2 eq	−0.0003	–	4.97E-04	0.0050	0.0541	0.1290	1.15E-04	–
	EU	kg PO_4 eq	0.0000	–	8.95E-07	0.0001	0.0009	0.0016	1.46E-06	–
	GWP	kg C_2H_4 eq	0.0460	–	3.61E-03	0.1521	1.5226	5.8053	2.00E-03	–
	ODP	kg CFC-11 eq	0.0000	–	2.23E-09	0.0000	0.0000	0.0000	3.32E-09	–
	HT	kg 1,4-DB eq	0.0386	–	3.92E-04	0.0713	0.3633	13.6470	2.89E-03	–
	FWAE	kg 1,4-DB eq	0.0012	–	2.31E-05	0.0021	0.0249	0.6071	2.73E-05	–
	MAE	kg 1,4-DB eq	2.3657	–	7.98E-02	8.9676	101.3243	1088.7389	1.13E-01	–
	TE	kg 1,4-DB eq	0.0003	–	4.28E-06	0.0003	0.0102	0.0967	1.84E-05	–
	PO	kg C_2H_4 eq	0.0000	–	1.30E-06	0.0000	0.0002	0.0013	5.89E-07	–
AC-H_3PO_4	AD	kg Sb eq	2.37E-05	–	2.14E-05	0.0010	0.0075	–	5.74E-05	0.0366
	TA	kg SO_2 eq	0.0001	–	5.35E-04	0.0042	0.0356	–	0.001	0.3914
	EU	kg PO_4 eq	3.21E-06	–	9.64E-07	0.0001	0.0006	–	4.59E-06	0.0123
	GWP	kg CO_2 eq	0.0034	–	3.89E-03	0.1267	1.0017	–	0.0081	3.6410
	ODP	kg CFC-11 eq	3.54E-09	–	2.40E-09	0.0000	0.0000	–	7.813	0.0000
	HT	kg 1,4-DB eq	0.0047	–	4.23E-04	0.0594	0.2390	–	0.0107	3.1712
	FWAE	kg 1,4-DB eq	0.0001	–	2.49E-05	0.0017	0.0164	–	0.0001	0.1400
	MAE	kg 1,4-DB eq	0.1498	–	8.59E-02	7.4688	66.6569	–	0.3987	482.933
	TE	kg 1,4-DB eq	5.044E-05	–	4.62E-06	0.0002	0.0067	–	5.46E-05	0.0286
	PO	kg C_2H_4 eq	6.65E-06	–	1.40E-06	0.0000	0.0002	–	1.84E-06	0.0024

reported by Dang et al. (2014) for bio-oil synthesized from corn stover via fast pyrolysis.

To evaluate the validity of the results, a comparison was made with similar studies. In this study, we obtained the general result that the main factor affecting all impact groups is the consumption of electricity. Several studies have evaluated bio-oil production from different biomasses and confirmed this conclusion. For example, Parascanu et al. (2018) investigated olive pomace volatilization in a fast pyrolysis system. Their findings indicated that GWP and HT were the most relevant categories, and the main environmental burdens come from electricity consumption. Peters et al. (2015a) evaluated bio-oil production via the fast pyrolysis of hybrid poplar and their results also confirmed this. In another similar work, Peters et al. (2015b) concluded that electricity consumption is a key component in determining environmental damage. Reducing energy consumption decreases the quantities of all impact categories.

3.2. Environmental assessment results of AC

Fig. 3 indicates normalized results of life cycle impact assessment of AC production using two activating agents ($ZnCl_2$ and H_3PO_4). As the results show, the order of the majority of the impact is as follows for AC-H_3PO_4: TA > MAE > TE > PO > AD > EU > GWP > FWAE > HT > ODP. The greatest environmental effect was related to terrestrial acidification (TA). The main factor affecting TA is the consumption of electricity and H_3PO_4 during the pyrolysis process of AC-H_3PO_4 (Table 4). In this study, the majority of electricity generation was based on fossil fuels, which leads to the production of acid pollutants such as SO_x and NO_x. Renewable energy should be used to reduce this effect. The MAE potential was ranked second among environmental impact categories. This effect shows all the toxic and poisonous substances release into the marine ecosystem during the product life cycle (Rosenbaum et al., 2008). For AC-H_3PO_4, the main contributor to this effect were heavy metals and metalloids (chromium, nickel, and arsenic) and hydrocarbons (benzene and PAH). Heavy metals are toxic and carcinogenic even at low concentrations. Mentioned contaminations are toxic and carcinogenic even at low concentrations (Jarup, 2003).

The magnitude of impact categories for AC-$ZnCl_2$ was MAE > TA > PO > TE > FWAE > HT > GWP > AD > EU > ODP, respectively. MAE was the major environmental impact. MAE associated with toxic substances such as heavy metal and polycyclic aromatic hydrocarbon that can be poisonous or cause health effects (Hertwich et al., 2001). The release of these compounds for AC-$ZnCl_2$ production (1201 kg 1,4-DB eq) was more than AC-H_3PO_4 (557 kg 1,4-DB eq). Zinc, chromium, cadmium, arsenic, benzene, and PAH were caused by toxicity in the life cycle of AC-$ZnCl_2$. These materials originated from the usage of electricity and zinc chloride in the process (Table 4).

The total energy demand to produce 1 kg of AC-$ZnCl_2$ and AC-H_3PO_4 in the slow pyrolysis system is 118.6 and 153.8 MJ, respectively. For AC-$ZnCl_2$, it included 104.5 of non-renewable energy and 14 MJ of renewable energy. For AC-H_3PO_4, it comprised 128.8 MJ of non-renewable energy and 24.9 MJ of renewable energy. Since the tar produced in the production process of AC can be burned like coal in a boiler to generate electricity and heat. It is a valuable co-product in the process. Tar can be considered a potential combustion oil and attractive alternative liquid fuel source for power generation. Due to its low sulfur content it is quite a promising biofuel from an environmental point of view, which could be directly combusted (Li and Suzuki, 2010). In addition, it has the ability to sequester carbon emissions due to arising from a renewable resource. Assuming the replacement of anthracite with tar, the carbon credits for AC-$ZnCl_2$ and AC-H_3PO_4 would be 3.17, 1.38 CO_2 per 1 kg of AC, respectively. On the other hand, if the tar were combusted directly as a fuel, electricity credits for AC-$ZnCl_2$ and AC-H_3PO_4 were found to be 7.26 and 3.16 MJ per functional unit. In addition, the quantities of heat credit for AC-$ZnCl_2$ and AC-H_3PO_4 were calculated 15.90 and 6.91 MJ/kg of AC. Regarding credits for tar, the net non-renewable energy for AC-$ZnCl_2$ and AC-H_3PO_4 was 95.43 and 122.94 MJ, respectively. Total CED of AC-H_3PO_4 (153.8 MJ) and AC-$ZnCl_2$ (118.6 MJ) were compared with commercial AC (242 MJ) (Bayer et al., 2005) and AC (158.3 MJ)

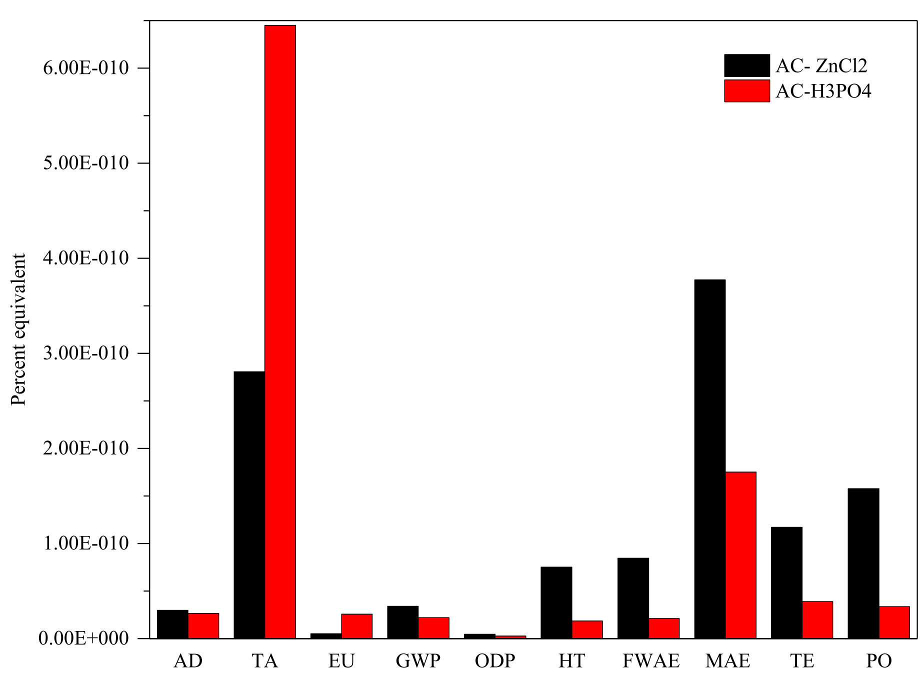

Fig. 3. Normalized environmental impacts of AC production via slow pyrolysis system.

derived from conifer wood (Gu et al., 2018). CED in this study is more than 36% lower than that of the commercial AC, whereas the nonrenewable energy decrease was more than 45.8%. The CED of AC from conifer wood was approximately similar to that of the AC-H_3PO_4 and higher than AC-$ZnCl_2$, whereas the nonrenewable energy reduction was more than 10%.

Environmental assessment results of AC-H_3PO_4 and AC-$ZnCl_2$ production were compared in Table 3 and Fig. 3 for each of the nine impact categories. GWP for AC-H_3PO_4 was calculated at 5.5 CO_2 eq/kg AC generated. This is less of that for AC-$ZnCl_2$ (8.5 CO_2 eq/kg AC generated). The GWP for AC production was mostly from the electricity use for the impregnation and pyrolysis processes. The TA impact from AC-H_3PO_4 production (0.43 kg SO_2 eq/kg AC generated) was notably higher than that for AC-$ZnCl_2$ production (0.188 kg SO_2 eq/kg AC generated). It is related to higher non-renewable energy consumed in the production process of AC-H_3PO_4 (128.8 MJ) compared to that of AC-$ZnCl_2$ (104.5 MJ) and as a consequence emission of higher acidic gas pollutants. Also, MAE for AC-$ZnCl_2$ production was more than that of AC-H_3PO_4 production (1201.5 kg 1,4-DB eq/kg AC generated vs 557.6 kg 1,4-DB eq/kg AC generated). This occurred due to heavy metals and hydrocarbon emitted in the AC production process. This was because $ZnCl_2$ was used as the activating agent in the process, which is more toxic than H_3PO_4 (Nsi et al., 2016). Additionally, the quantities of the other impact categories, e.g. AD, ODP, FWAE, MAE, TE, and PO of AC-H_3PO_4 were much less than AC-$ZnCl_2$. Therefore, AC-H_3PO_4 results suggest a potential eco-friendly product derived from eucalyptus wood.

The results of this study have been compared with those reported by Gabarrell et al. (2012) and Hjaila et al. (2013), concerning the life cycle assessment of AC production (Table 3). As can be seen from this table, GWP and HT were the most important environmental impact categories in the life cycle of AC across all studies. The HT of the AC-$ZnCl_2$ process was higher than the impacts of other AC. This can be attributed to the use of $ZnCl_2$ as an activating agent when generating AC from eucalyptus wood. As Hjaila et al. (2013) stated, different inputs, assumptions, scope, fabrication scales, and energy sources were applied to evaluate the life cycle of AC. Hence, a comparison between the impact categories is difficult. For example, for AC production, Hjaila et al. (2013) used H_3PO_4 as an activating agent and olive waste as feedstock while Gabarrell et al. (2012) were based on the physical activation of hard coal. Additionally, the GWP of AC-$ZnCl_2$ and AC-H_3PO_4 was less than the impact of olive waste AC. This is due to the elimination of the drying and crushing of biomass process from the product life cycle and as a result less electricity consumption in the system.

3.3. Comparison between bio-oil and AC

3.3.1. Comparison with CML baseline method

As stated in Section 2.1, in order to manage eucalyptus wood waste, two scopes including bio-oil production and AC synthesis, were considered. However, comparison between scenarios is desirable. A comparison between the life cycle results of these scenarios based on the CML method was shown in Table 3. As observed in Table 3, there is a significant difference between the bio-oil and AC scenarios. Bio-oil was a better option, in terms of all impact categories. On the other hand, AC production alternative, especially using zinc chloride exhibited more considerably quantities of AD, GWP, ODP, HT, FWAE, MAE, TE, and PO, compared to bio-oil.

Although the LCA provides a range of indicators, global warming and energy are more important criteria when the most convenient energy systems are projected (Dufour and Iribarren, 2012; González-García et al., 2012; Yee et al., 2009). In this regard, Table 3 shows that the bio-oil scenario potentially has a better global warming performance than activated carbon. The bio-oil outline is more related to high renewable energy demand (84.1%). In order to clarify the energy performance of both scenarios, the total cumulative energy demand for 1 kg of product was calculated. The total cumulative energy demand for bio-oil, AC-$ZnCl_2$, and AC-H_3PO_4 is 16, 118.6, and 153.8 MJ per functional unit, respectively. 88.1% and 83.7% of the total cumulative energy demand of AC-$ZnCl_2$, and AC-H_3PO_4 associated with non-renewable energies, respectively, while this was 15.8% for bio-oil.

3.3.2. Comparison with the PEF method

The PEF method was used to enhance the comparability of the environmental assessment of pyrolysis products from eucalyptus wood waste. Fig. 4 shows the normalized contributions of the impact categories to the total PEF. The lowest impact product was bio-oil with a PEF of 0.115. The highest PEF obtained for AC-$ZnCl_2$ (7.276). The PEF of AC-H_3PO_4 (1.43) was 5.1 times lower than AC-$ZnCl_2$. The Non-cancer human health effects (NCHHE) and cancer human health effects (CHHE) contributed 85.8 and 37.5% to the final result in AC-$ZnCl_2$ and AC-H_3PO_4, respectively. Climate change (CC) dominated the total environmental impact (44%) in bio-oil. The high PEF results of AC-$ZnCl_2$ are attributed to using $ZnCl_2$ in the synthesis process and lower production yield. The low ranking of bio-oil can be related to the lower energy consumption, higher production yield compared to the other products and non-use of chemicals in the synthesis process.

Table 5 compared the PEF results by normalized impact categories. Across all analyzed products, NCHHE, CHHE, and ecotoxicity freshwater (ETF) caused the highest impact. In the AC-$ZnCl_2$, impregnation with $ZnCl_2$ was the main drive in human and freshwater toxicity. In addition, electricity production for usage in the synthesis stage was an important contributor to human toxicity cancer effects. The lowest impacts happened in ozone depletion (ODP) and resource use, mineral, and metals (RUMAM) for which the contribution was different between all products. For example, the quantities of RUMAM in AC-$ZnCl_2$ and AC-H_3PO_4 were almost 406 and 689 fold that in bio-oil.

3.4. Sensitivity analysis

Sensitivity analysis is performed to evaluate the impact of environmental impacts due to the change in process parameters. “What-if” sensitivity analysis can examine how variations in various input parameters can affect output and results (Pianosi et al., 2016). Similar to other works (Arena et al., 2016; Chan et al., 2016; Heng et al., 2018; Hjaila et al., 2013), electricity consumption is a key factor in slow and fast pyrolysis and has a significant effect on LCA results. Hence, a variation of ±20% was assumed in the total electrical energy consumption associated with bio-oil and AC production via fast and slow pyrolysis. Moreover, the quantity of activating agent and the flow rate of N_2 affected most of the impacts in slow and fast pyrolysis, respectively. Hence, these variables were also investigated.

The sensitivity analysis results for all three products (AC-$ZnCl_2$, AC-H_3PO_4, and bio-oil) are shown in Fig. 5. As is evident from these figures, reducing electricity consumption in the fast and slow pyrolysis process decreased the environmental impact data and resource consumption, while its increase presented a reverse trend. In other words, a 20% reduction in electric power consumption in the system leads to the biggest decrease in EU, TE, and TE impact categories for AC-$ZnCl_2$, AC-H_3PO_4, and bio-oil, respectively. The rising trend in environmental burdens was observed for a 20% increase in electricity utilization in both systems. In the fast pyrolysis system, with a 20% increase in reaction temperature (from 450 to 550 C), the following results were obtained: the bio-oil yield decreased from 50.8 to 44.64 wt% while the amount of gas

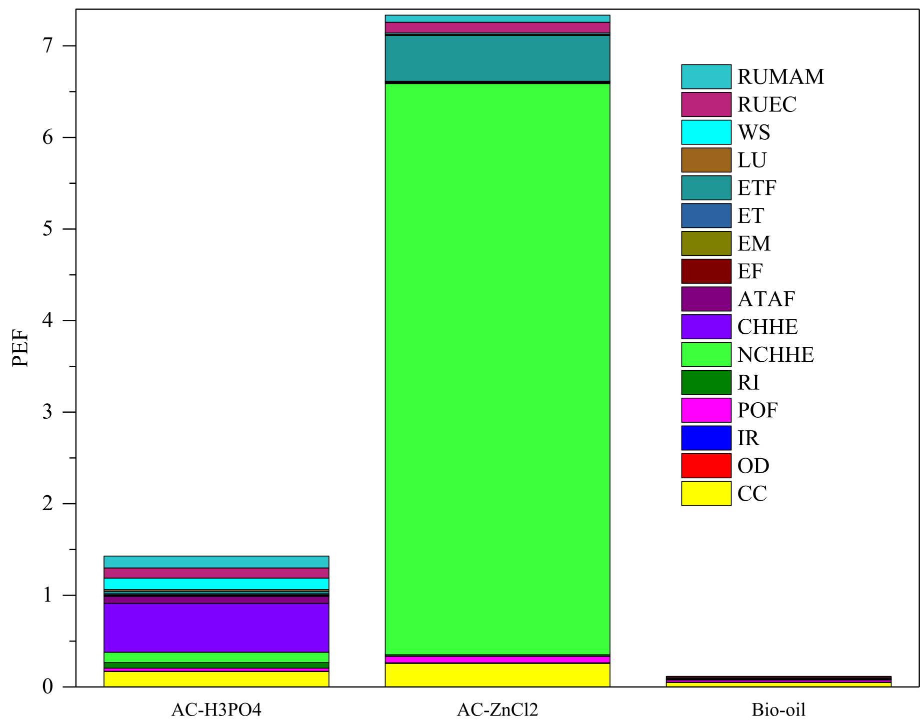

Fig. 4. Normalized PEF results per 1 kg of product.

Table 5
Comparison of PEF result by normalized impact categories.

Impact category	Abbreviation	AC-H_3PO_4	Bio-oil	AC- $ZnCl_2$
Climate change	CC	0.00078	0.0002	0.0012
Ozone depletion	ODP	2.94E-05	0.000	5.95E-05
Ionizing radiation, HH	IR	7.86E-05	0.00003	2.08E-05
Photochemical ozone formation, HH	POF	0.0006	0.0004	0.0015
Respiratory inorganics	RI	0.00067	0.00007	0.00018
Non-cancer human health effects	NCHHE	0.00614	0.00007	0.338
Cancer human health effects	CHHE	0.02507	0.00004	−0.00275
Acidification terrestrial and freshwater	ATAF	0.00124	0.00009	0.00015
Eutrophication freshwater	EF	0.00028	0.00001	0.0002
Eutrophication marine	EM	0.00021	0.00002	0.00012
Eutrophication terrestrial	ET	0.00037	0.00003	0.00013
Ecotoxicity freshwater	ETF	0.00138	0.00002	0.02607
Land use	LU	0.00022	0.00012	0.00016
Water scarcity	WS	0.00148	0.00001	0.00017
Resource use, energy carriers	RUEC	0.00132	0.00017	0.00139
Resource use, mineral and metals	RUMAM	0.00172	0.00000	0.00101

increased from 29.43 to 39.46 wt%. The char quantity decreased from 19.72 to 15.89 wt% (Heidari et al., 2014a). It can be concluded that a 20% increment in electricity consumption not only enhanced the values of environmental impact categories but also decreased the bio-oil yield and increased pyrolytic gas.

The flow rate of N_2 was another key parameter in bio-oil production. A variation of ±20% of N_2 gas flow in fast pyrolysis process leads to a maximum 17.8% reduction and a 14.03% increment in the environmental consequences, in particular, TA and ODP, respectively (Fig. 6). With 20% rise in N_2 gas flow rate (from 11.1 to 13.32 L/min), the bio-oil yield increased from 50.8 to 60.48 wt% while the char (19.72−12.6 wt%) and gas (29.43−26.9 wt%) efficiencies decreased (Heidari et al., 2014a). Generally, although the 20% enhancement in N_2 gas flow resulted in 15.8 improvements in the bio-oil production, it corresponds to a 0.3−17.8% increase in almost all environmental burdens.

Sensitivity analysis was also evaluated by variation of ±20% of the quantity of the chemical activating agent. Fig. 6 shows that reducing the amount of activation agent in the slow pyrolysis process resulted in a considerable 19% reduction in the environmental impacts, especially in HT, MAE, and FWAE for AC-$ZnCL_2$ and EU, HT, and TA for AC-H_3PO_4. Furthermore, the increment of activating agents up to 20% leads to a maximum increase of 19% in the impact groups. On the other hand, a 20% reduction in the amount of H_3PO_4 had a significant effect on the obtained AC properties; surface area decreased from 2117 to 1889 m^2/g and total pore volume declined also from 1.5 to 1.1 cm^3/g. For $ZnCl_2$ activating agent, this reduction also leads to a drop in surface area from 2108 to 1884 m^2/g and total pore volume from 1.05 to 0.9 cm^3/g (Heidari et al., 2014b). Therefore, it can be concluded that reducing the amount of activating agent by up to 20% in the process of AC production, while reducing the environmental burden, the quality of the AC was diminished.

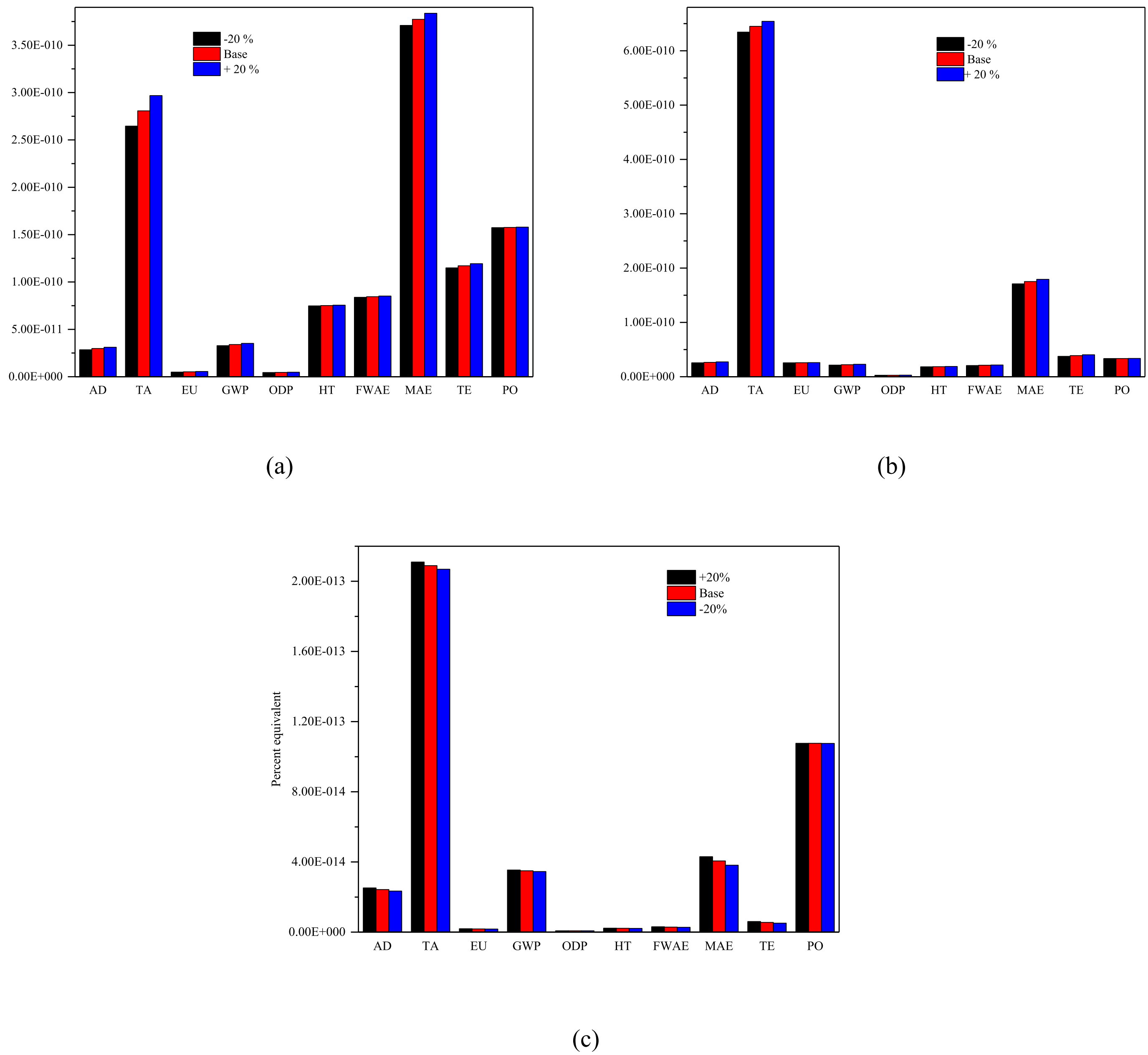

Fig. 5. The results of sensitivity analysis of the impact categories by the variation (±20%) of the electric energy consumption versus the baseline case, (a) AC-$ZnCl_2$, (b) AC-H_3PO_4, and (c)Bio-oil.

3.5. Implications

This study assessed the environmental impacts of producing bio-oil and AC from eucalyptus wood waste using LCA methodology. The findings have significant implications that may assist policymakers to develop appropriate solutions for both the management of wood waste and its recycling. Based on the results, policymakers are suggested to consider the type and amount of environmental impacts of products in order to choose the most eco-friendly one. Marine ecotoxicity was recognized as one of the most important environmental impacts of these products. Therefore, the need arises to reduce these effects by replacing consumed fossil fuels with by-products in these processes, such as biochar and tar. Air pollution is one of the environmental burdens that are crucial in determining the proper waste management strategy. Photochemical oxidants, as one of the major air pollutants, were another major problem of these products, which greatly affects the type of product. For example, bio-oil had a much lower quantity of photochemical oxidants than AC. The findings could also be helpful for manufacturers or investment communities who are to target the production of AC with less environmental load. According to the Environmental Footprint of Products, carbon produced with acid (H_3PO_4) is a better option. Finally, bio-oil production from eucalyptus wood residue through a fast pyrolysis process has a much better environmental performance than AC. Therefore, bio-oil is considered as an environmentally friendly product and fast pyrolysis is a green pathway which is recommendable for the recycling of wood waste.

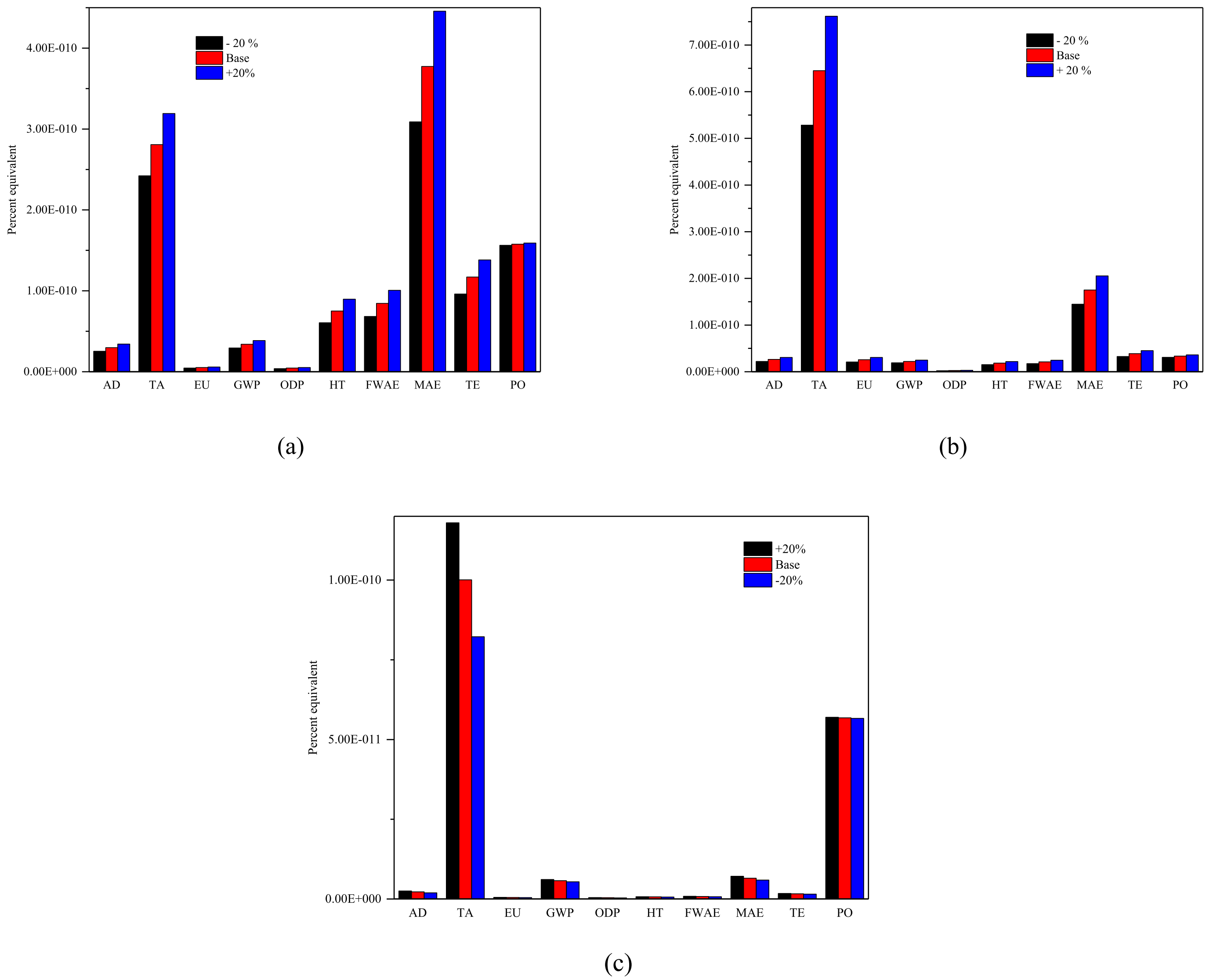

Fig. 6. The results of sensitivity analysis of the impact categories by the variation (±20%) of other main factors versus the baseline case, (a) AC-$ZnCl_2$, (b) AC-H_3PO_4, and (c)Bio-oil.

3.6. Limitations and recommendations

This LCA study, like other studies (Chan et al., 2016; Dang et al., 2014; Hjaila et al., 2013; Sepúlveda-Cervantes et al., 2018), was performed based on the general conceptual industrial processes of fast and slow pyrolysis. Therefore, some real and technical data such as electricity consumption have not been used. Industrial equipment usually has higher energy efficiency and hence less power consumption. Hence, there is a difference between these two types of actual and hypothetical data. In addition, since the purpose of this research is to compare the two options (bio-oil and activated carbon production) for wood waste management, use phase in the life cycle have been eliminated. In other word, the system boundary excludes the utilization of bio-oil and AC. Therefore, cradle-to-grave scope is recommended for future study. The environmental impacts were calculated by the CML method in this study. It is recommended that other comprehensive assessment methods such as ReCipe should be used for upcoming works. Finally, as reported in other studies (Chan et al., 2016; Fortier et al., 2014), due to the different system boundaries, different technical assumptions, data, and life cycle assessment methods, comparison the results of this study with literature are difficult.

4. Conclusion

A life cycle assessment of bio-oil and AC production from eucalyptus wood waste via fast and slow pyrolysis was conducted. The findings showed that each of these products created different values of environmental impacts. In the bio-oil production process, the most important environmental impacts were TA, PO, and MAE. The principal reasons for that were the use of fossil fuels to provide the energy needed for drying and decomposing the biomass. In the AC production process, MAE and TA were major environmental loads of the system. In addition to chemical activation substances, fossil fuel was the main cause of creating these affected groups. Moreover, the type of chemical activating agent used during the AC generation ($ZnCl_2$ and H_3PO_4) had a great influence on the magnitude of impact categories. $ZnCl_2$ not only decreased the yield of AC production but also increased the value of ecosystem toxicity. Furthermore, according to the PEF method, bio-oil production from eucalyptus wood residue had a better environmental performance than AC. For example, the global warming potential of AC production is more than 3.8 times that of the generation of bio-oil. In addition, bio-oil production not only reduces the fossil fuel demand and abiotic resources depletion but also produces biochar as a co-product, which diminishes the environmental burdens.

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