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# Life cycle assessment of bio-based levoglucosan production from cotton straw through fast pyrolysis

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## Abstract:

This study aimed to evaluate the environmental impacts (i.e. global warming potential (GWP) and resource depletion (RD)) of the bio-based levoglucosan production process through fast pyrolysis of cotton straw via life cycle assessment (LCA). An LCA model consisting of feedstock transportation, biomass pretreatment, fast pyrolysis, bio-oil transportation, bio-oil recovery and levoglucosan extraction was developed. Results indicated that GWP and RD of bio-based levoglucosan production were approximately 2 and 32.5 times less than that of the petroleum-based counterpart. Sensitivity analysis showed that the GWP and RD of levoglucosan production were highly sensitive to plant size, HCl usage, cooling energy, levoglucosan yield and bio-oil yield. The results of this research could provide a framework for robust decision making at an industrial level, which is useful for the commercial-scale production of levoglucosan.

**Keywords:** Levoglucosan; Life cycle assessment (LCA); Bio-based chemicals; Bio-oil; Global warming potential (GWP); Resource depletion (RD)

## 1. Introduction

Oil, coal, natural gas and other fossil fuels are the main sources of energy and synthetic materials in modern industry and life. While, depletion of fossil fuel has attracted increasing attention with the annually growing energy demand in the world (Wang et al., 2016b). In addition, the combustion of fossil fuels also emits a huge amount of $CO_2$ and leads to global warming. Nevertheless, the demand for petroleum-based chemicals and materials is still increasing (Isikgor & Becer, 2015). Nowadays, conserving resources and protecting the environment are two important topics that concerned by governments. The UN climate panel has aimed for a reduction in greenhouse gas emissions by 50–80% by 2050 (Dhyani & Bhaskar, 2018). New sources for energies and materials are being intensively investigated, and it is clear that future growth in the energy sector is primarily in the new regime of renewable (Ellabban et al., 2014; Vienescu et al., 2018).

Among the available renewable resources, biomass contains carbon and hydrogen that can be converted to fuel and chemicals (Alonso-Farinas et al., 2018). With different treatments, such as thermal, biological, mechanical, and physical processes, biomass can be converted to high value-added chemicals (Ubando et al., 2019). Thermal chemical conversion has higher efficiency and potentially lower cost compared to other treatments, and therefore very promising (Zhao et al., 2017).

Levoglucosan, 1,6-anhydro-β-D-glucopyranose, is an important chemical building block that can be used for the manufacture of plastics, surfactants, biodegradable polymers, and other chiral bioactive natural products (Rover et al., 2019; Jiang et al., 2019). In general, levoglucosan is synthesized from D-glucose by attaching the OH group to form a second ring structure (Rover et al., 2019). However, the high price of levoglucosan through the conventional method restricts the development and application in the chemical industry (Rover et al., 2019; Zheng et al., 2018). An alternative pathway for levoglucosan production is through the thermal deconstruction of cellulose. Fast pyrolysis of inexpensive lignocellulosic biomass has the potential to produce large quantities of levoglucosan with commercially attractive prices (Wang et al., 2019b). However, it is still uncertain whether levoglucosan from biomass is more environmentally friendly or greener than the petroleum-derived levoglucosan.

The environmental impacts of obtaining products from a pyrolysis process can be analyzed using life cycle assessment (LCA). LCA offers a standardized tool for environmental comparisons among different technological routes (Vienescu et al., 2018). Although LCA of pyrolysis has been conducted for many years, there is still a lack of LCA investigation on bio-based chemicals from fast pyrolysis. A number of LCA studies on biofuels obtained from fast pyrolysis have been carried out. Peter et al. (2015) simulated a pyrolysis plant and biorefinery for fast pyrolysis of hybrid poplar. Results showed greenhouse gas (GHG) savings of 54.5% for the produced fuel mix compared to conventional gasoline and diesel. Vienescu et al. (2018) conducted a study on pyrolysis of corn stover and found the carbon dioxide equivalent ($CO_{2eq}$) emissions to be 6000 g $CO_{2eq.}$/kg of upgraded fuel, which was greater than the emissions arising from the use of diesel fuel.

This study aimed to analyze the environmental impacts of levoglucosan production from biomass as compared with that of petroleum-based production, so that a more informed comparison can be made to guide future research and development on levoglucosan production. Moreover, the uncertainty of LCA was investigated based on a series of sensitivity analysis. This study will help to identify the bottlenecks and potential improvements in the sustainable development of the levoglucosan production industry.

## 2. Methods

LCA was carried out with GaBi LCA software using TRACI 2.1 impact assessment method. The impact categories considered in this study include global warming potential (GWP) (as kg $CO_{2\ eq.}$), acidification potential (as kg $SO_{2\ eq.}$), eutrophication potential (as kg $N_{\ eq.}$), fossil fuels resource depletion (RD) (as MJ surplus), ecotoxicity potential (as CTUe), human health impacts (carcinogenic/non-carcinogenic) (as CTUh), photochemical ozone formation (as kg $O_3$), ozone depletion potential (kg CFC-$11_{eq.}$), and respiratory effects (kg PM 2.5 $_{eq.}$). GWP and RD were discussed in further details as these are currently the most relevant impact categories in China environment, caused by the Chinese plants (Li et al., 2018).

## 2.1 Goal and scope definition

The goal of this study was to evaluate the environmental performance of levoglucosan production via fast pyrolysis. The environmental footprints of all input processes of the entire life cycle from raw material (cotton straw) transportation to the final product (levoglucosan) were included in this study. Emissions from cotton production were not considered here as this study focuses on the levoglucosan production from field edge to biorefinery. For the analysis, the whole system was divided into six subsystems. According to Figure 1, the subsystems include feedstock transportation unit (process 1), feedstock pretreatment unit (process 2), fast pyrolysis unit (process 3), bio-oil transport unit (process 4), bio-oil refinery unit (process 5) and levoglucosan extraction unit (process 6). The operation time of levoglucosan production was considered as 300 days per year, with a lifetime of 20 years. The production rate was considered as 200,000 t/y cotton straw. The data of fast pyrolysis and refinery units were collected from our previous work, which was simulated in Superpro Designer v9.5 (Wang et al., 2019b). Data for the remaining units were mainly retrieved from the literature (Wang et al., 2016a; Zheng et al., 2018) and Ecoinvent database v3.6. The environmental performance of levoglucosan production was evaluated following the LCA approach. The functional unit (FU) used in this work was 1kg of levoglucosan. The details on input and output attributes were provided in table 1, table 2 and will be briefly discussed in the following sections.

## 2.2 Life cycle inventory (LCI)

### 2.2.1 Transportation (Process 1 and Process 4)

Cotton is a local resource which can be easily found in the rural area, and small-scale pyrolysis plants were assumed to be located in Shaanxi province, China, which was close to the plantation sites for minimizing transport distance. The average delivery distance was calculated based on Eq. (1)(Zhang et al., 2013; Zheng et al., 2018).

$$r = \frac{1}{6}\tau\sqrt{\frac{F}{Yf}\left(\sqrt{2} + Ln(1+\sqrt{2})\right)} \tag{1}$$

where F is the feedstock delivered annually to the plant; Y is the annual yield of feedstock; f is the fraction of acreage around the plant devoted to feedstock production; $\tau$ is the ratio of the actual distance to the straight-line distance from the plant.

The distance from the cotton field to the pyrolysis plant was calculated to be 4 km. Storage of the harvested cotton straw took place at the plantation site without any drying (an average 10% moisture as delivered to the plant was therefore assumed) and then the biomass was shipped to the plant site by a truck just in time. Possible natural drying on the site during open-air storage was not considered. An average transport distance of 100 km was assumed from the pyrolysis plants to the biorefinery plant, the biorefinery was assumed to be part of an existing refinery installation due to economic reasons. All of the transportation in this model was assumed using trucks. The diesel consumption for transportation was affected by several factors, such as the type and speed of the trucks and the weight of the products (Naujokienė et al., 2019).

In this study, the effect of the transportation was only dependent on the weight of freight (cotton straw/bio-oil) and the average two-way distance between the farmland and different facilities (Evangelisti et al., 2015).

### 2.2.2 Feedstock pretreatment (Process 2)

The cotton straw was chopped using a chopping machine during the pretreatment process. After chopping, the cotton straw was fed into a reactor to wash out alkali and alkaline earth metals, and ash. Then the cotton straw and the acid liquid were transferred into a filter. Before being transferred to the fast pyrolysis unit, a drying machine was used to reduce the moisture content of cotton straw to 5wt%. Waste 1 mainly contained chlorides (Wang et al., 2016a), thus the "chlorides" from Ecoinvent database was used to represent the outputs. In LCA model, the chopping machine with a capacity of 3.3 $m^3/h$, and the reactor with a capacity of 16,000 $m^3$. Other detail data of energy and mass required for pretreatment were shown in table 1 and table 2.

### 2.2.3 Fast pyrolysis (Process 3)

In fast pyrolysis system, treated cotton straw and inter gas were fed into a fluidized reactor to produce bio-oil, biochar, and non-condensable gases. In this study, it was assumed that no further process was conducted to biochar. The biochar was considered as an independent product and a share of the environmental impacts from the fast pyrolysis process had to be allocated to biochar. Since all products had energetic uses, allocation was carried out according to their energy content (Peters et al., 2015). Based on heating values of bio-oil and biochar, the corresponding allocation percentages for bio-oil and biochar were calculated as 68.47% and 31.53%, respectively. For non-condensable gas, it was assumed that it will be recycled in this model, so the impact on the environment will not be considered.

As mentioned before, assume that all the gas fraction was recycled by burning on site for process heat generation. Based on the real situation of China, most of the installed fast pyrolysis plants for biomass are using fluidized bed reactor (Deng et al., 2014). So, in this LCA model, the "fluidized bed reactor" dataset from Ecoinvent v3.6 was used. The energy consumption of this process was shown in table 1.

### 2.2.4. Refinery (Process 5 and Process 6)

The refinery consisted of two principal processing steps: bio-oil recovery and levoglucosan extraction. In bio-oil recovery unit, the bio-oil was converted via several steps of extraction into raw levoglucosan. Water and $Ca(OH)_2$ were added to bio-oil to remove some colloids, aromatic compounds by physical and chemical flocculation. Then, the evaporation machine was used to obtain raw levoglucosan. For levoglucosan extraction unit, the raw levoglucosan was dissolved into EtOAc to form an ethyl acetate phase and water phase. The vacuum evaporation machine was used to remove the EtOAc solution, and levoglucosan was obtained after a dryer machine. The data for waste 2 and waste 3 were collected based on similar plants in China and our previous experimental findings in laboratory scale (Wang et al., 2016a). The energy data was collected from the calculation of equipment power and use time (Table 1).

### 2.3 Sensitivity analysis

Sensitivity analysis is performed to examine the effects of individual input parameters on the environmental impacts of levoglucosan production. The input parameters were selected based on the potential variation in the levoglucosan production. Sensitivity analysis is performed based on a ±20% change on average levels of individual inputs (Wang et al., 2019a; Wang et al., 2019b). Several parameters, including levoglucosan yield, bio-oil yield, the consumption of electricity, steam, cooling energy, HCl usage and $Ca(OH)_2$ usage, days of plant operation and plant size, were considered for the sensitivity analysis in this study.

## 3. Results and discussion

### 3.1 Environmental assessment of GWP and RD

The environmental impacts calculated for six subprocesses are shown in Figure 2 and Figure 3. Figure 2a and 2b show that the production of cooling energy was the leading consumer of RD in the fast pyrolysis unit, whereas the fast pyrolysis unit had the highest contribution to the whole processes based on RD. According to our previous research, the fast pyrolysis unit required a large amount of cooling energy to separate condensable and non-condensable gases (Wang et al., 2016a). In general, cooling energy is usually obtained by a cooling tower, which demands to consume a large amount of electricity, fossil fuel and water (Chaiyat et al., 2020), and in which, electricity is usually generated by coal combustion (Chen et al., 2016). Except for the fast pyrolysis unit, the bio-oil recovery unit also had high environmental impacts in terms of RD, which was mainly because of the material and energy consumptions related to the manufacture of equipment (Li et al., 2018). In addition, the production of chemicals also consume a lot of fossil fuels and pollute the environment seriously (Wang et al., 2019a). The increasing demand for fossil fuel may lead to a high weight of RD damage.

GWP assigns a value to the amount of heat trapped by a certain mass of a gas relative to the amount of heat trapped by a similar mass of $CO_2$ over a specific period of time (Yang et al., 2018). The assessment shows in Figure 3a reveal that the bio-oil recovery unit contributed the most to GWP by 37% followed by biomass pretreatment unit by 34%. Unlike RD, the biomass pretreatment unit was found to be a particularly impactful phase in GWP, which involved several steps including feedstock chopping, acid washing and drying. Contribution to the GWP in this unit was mainly due to the consumption of HCl during acid washing (Figure 3b). HCl consumes amount of fossil fuel due to its complex production process. In addition, during the production of HCl, large amounts of $CO_2$ and $CH_4$ are produced (Sebastiao et al., 2016). According to The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, the GWP of $CO_2$ is defined as 1, $CH_4$ is about 28 and $N_2O$ is about 265 (2014, www.ipcc.ch). Thus, optimize the use of HCl can alleviate the greenhouse effect. A similar finding was reported by Sebastião (2016), who found that reducing the usage of HCl during the production of bioethanol significantly improved the carbon footprint.

In general, conventional levoglucosan is usually considered as a petroleum-based product, so a large amount of fossil fuel will be consumed and increased the greenhouse gas in the atmosphere. This paper discussed the changes in environmental and energy profiles as a result of producing levoglucosan through bio-based route instead of the petrochemically presented in this paper. The values of GWP and RD of petrochemically produced levoglucosan were obtained from an LCA study by Zheng et al. (2018). Results indicated that petroleum-based levoglucosan had higher values of GWP and RD in comparison to bio-based levoglucosan by 195% and 3254%. From that, the petrochemical process was highly energy intensive. In addition, during the petrochemical synthesis process of levoglucosan, in order to form a heterocyclic structure, more materials and energy consumption were needed (Zheng et al., 2018). The GWP and RD of biochar were 0.38 kg $CO_2$ eq./kg biochar and 0.46 MJ surplus/kg biochar, respectively. Since the biochar was a by-product in this model, its environmental impacts were not further discussed in this paper.

Other studies involving bio-based chemical production did similar comparsions. Bio-succinic acid had lower GWP and non-ren cumulative energy demand (CED) values in comparison to petroleum-based succinic acid by 385% and 1045%, respectively (Moussa et al., 2016). Tsiropoulos et al. (2015) conducted that GWP of partially bio-based polyethylene terephthalate was similar to petrochemical production (±10%) and RD was lower by up to 10%, partly due to the low bio-based content of the polymer. It was obvious that extracting petroleum-based resources consumes a large amount of fossil fuel. However, heavy use of fossil fuel directly increases the greenhouse gases, air pollution, smog in urban areas and water pollution by oil spills, in addition, it also indirect effects weather conditions, such as acid rain, global warming, climate changes and so on (Nanda et al., 2015). However, it is worth mentioning that the GWP of bio-based chemicals usually calculated in different ways. Some researches will consider the credit from biomass since biomass is considered as carbon neutral (Annamalai et al., 2018). For example, woody-biomass based polyethylene terephthalate (PET) bottles had 21% less GWP than their fossil-based counterparts. If no displacement credits were considered, forest residue bottles would have higher GWPs than fossil bottles (Chen et al., 2016).

## 3.2 Other environmental impact categories

Other impact categories of the TRACI impact assessment method can be approximately divided into two aspects, human health (human health carcinogenic, human health non-carcinogenic and respiratory effects), and ecosystem (acidification, eutrophication, ecotoxicity, ozone depletion, and photochemical ozone formation). The results were shown in table 3.

For the human health category, the contaminants can be classified as carcinogens and non-carcinogens, for carcinogens, they can cause both carcinogenic and non-carcinogenic effects on organisms (Yu et al., 2014). For levoglucosan production, the construction of equipment (such as reactor, dryer etc.) contributes some hazardous substances to human health. “Respiratory effect” usually refers to the environmental impacts caused by slash pile burning (Du et al., 2018). It is usually calculated by converting $SO_2$, $NO_x$ and PM2.5$_{eq.}$ in PM 2.5$_{eq.}$ emissions using the conversion factors (Wang et al., 2015). Nowadays, high levels of PM 2.5 are a serious environmental, social and economic burden that has attracted great public attention. Studies showed that the negative relationship between PM 2.5 and chronic health effects, certain concentrations PM 2.5 may cause lung cancer, ischemic heart disease, asthma and other health complications (Liu et al., 2018b; Maji et al., 2018). Thus, seeking for green methods to produce fuels and chemicals is necessary. The respiratory effects for levoglucosan production is relatively environmental-friendly compared with other bio-products (Rover et al., 2019).

For the ecosystem category, "acidification" is commonly related to the atmosphere pollution by S and N and "eutrophication" covers the potential impacts of elements, mainly N and P, which may above the environmental level  (Li et al., 2018). "Ecotoxicity" impact is mainly related to wastewater treatment. The use of chemicals in biomass pretreatment and bio-oil recovery units give significant contributions to the ecological environment. Among these chemicals, HCl has the biggest impact on the environment and human people. Chlorine atom can participate in catalytic ozone destruction cycles in the stratosphere, however, the stratospheric ozone layer plays a vital role in shielding harmful ultraviolet (UV) radiation-emitting to the surface of the Earth. As shown in table 3, producing 1kg levoglucosan can generate $5.4*10^{-7}$ kg CFC-11$_{eq}$.

### 3.3 Sensitivity analysis

This section described the outcome of the sensitivity analysis based on GWP and RD of the levoglucosan production process ranging from 80% to 120%. As shown in Figure 4, the most sensitive parameters on GWP and RD were identifying as plant size, levoglucosan yield, bio-oil yield, cooling energy consumption and HCl usage. The variation in plant size resulted in variation in the consumption of chemicals and thus directly affected the environment. However, the relatively higher variation in levoglucosan yield from bio-oil had positive impacts on the GWP, which may because increasing the levoglucosan yield from bio-oil will decrease the waste so that consequently lower the environmental impacts. As discussed in section 3.1, cooling energy and HCl usage were the most sensitive inputs for GWP and RD, which could harm the environment with the amount of input increase. Thus, environmental issues could be alleviated with the appropriate decrease in the amount of cooling energy and HCl usage. Figure 4 also interpreted that increasing bio-oil yield will increase the use of fossil fuels and thus the emission.

### 3.4 Limitation of the study

This LCA study, like other studies (Dang et al., 2014; Vienescu et al., 2018), was performed based on the general conceptual industrial process of fast pyrolysis. Some of the limitations of this research include uncertainty in the data collected from the literature, for example, the electricity and energy consumption of industrial equipment. Hence, there is a difference between these two types of actual and hypothetical data. In addition, this study mainly focusses on GWP and RD, while solving one environmental problem may often create or aggravate another one, thus, a comprehensive LCA analysis may be necessary in order to avoid environmental problem shifting. Future studies are also needed to investigate the uncertainty analysis of this study, in addition, the way to produce levoglucosan still needs to be improved in order to minimize environmental impacts for the purpose of green economic profit analysis.

## 4. Conclusion

This study focused on the environmental impacts of levoglucosan production from cotton straw through fast pyrolysis. The LCA results showed that bio-oil recovery and biomass pretreatment units were major contributors to GWP (4.57kg $CO_2$ eq./kg levoglucosan), while fast pyrolysis and bio-oil recovery units consumed a large portion of RD (5.52 MJ surplus/kg levoglucosan). Sensitivity analysis revealed that HCl usage, cooling energy, levoglucosan yield, bio-oil yield and plant size were major factors affecting the environment impacts of whole system. Levoglucosan production from biomass had a better environmental performance than petroleum-based production and it also had a good prospect for commercial application.

## Acknowledgement

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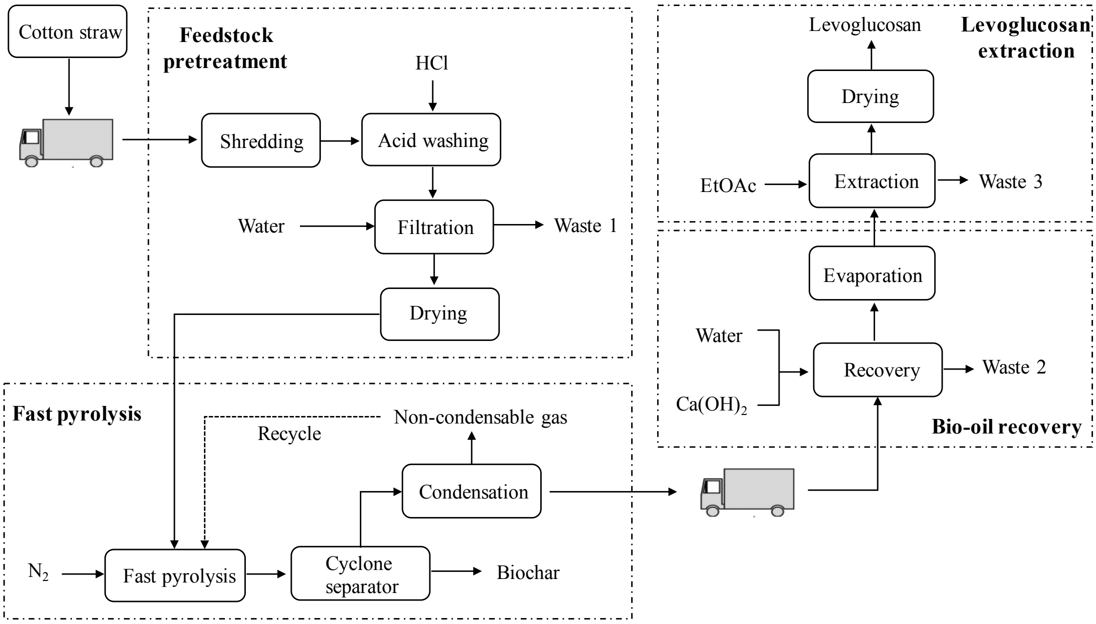


Figure 1. System boundary of levoglucosan production from cotton straw. (Waste 1 mainly includes most chlorides; Waste 2 mainly includes $CaCO_3$, aromatic compounds and ester. Waste 3 mainly includes calcium salts, ester and water)

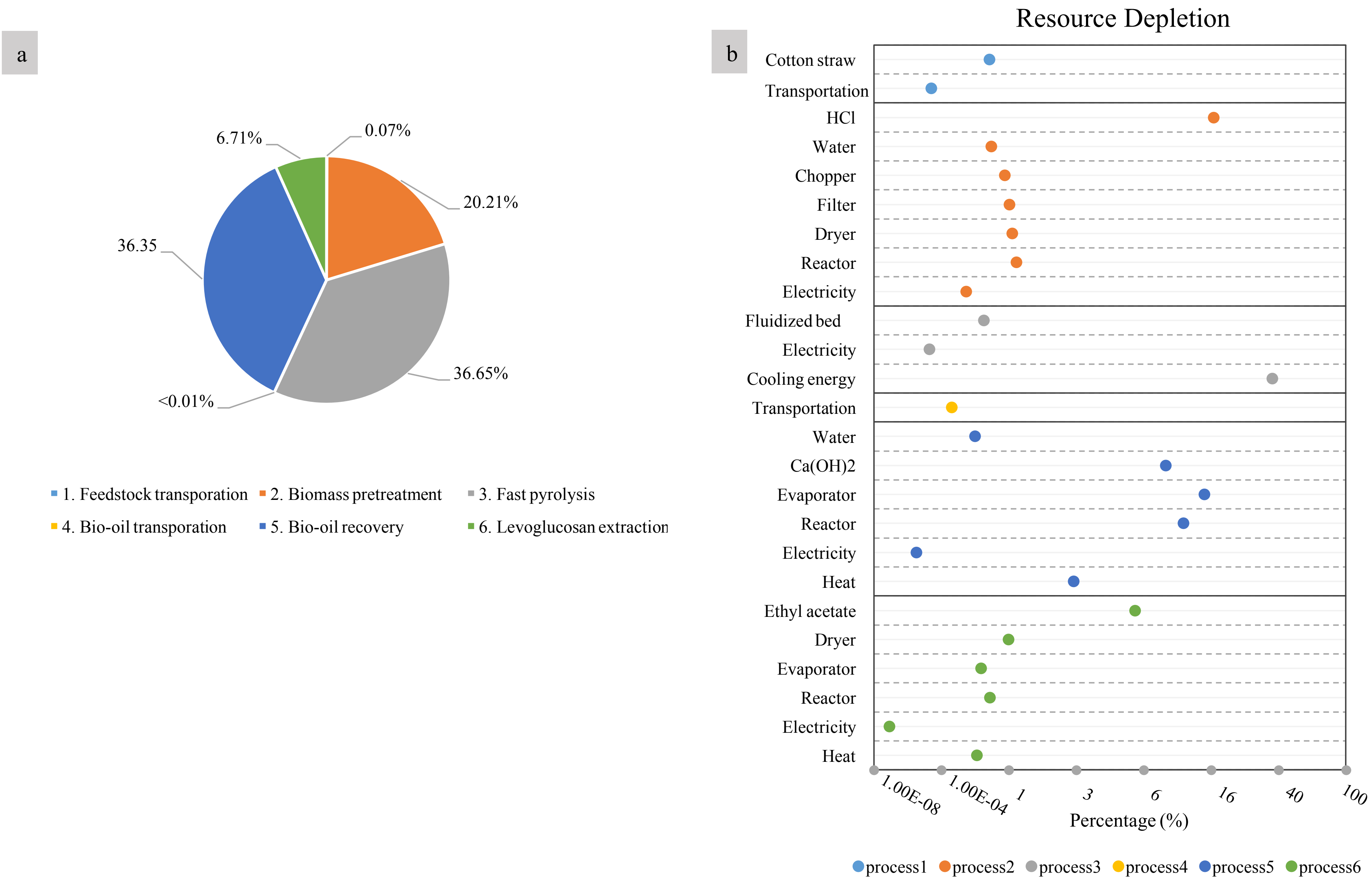
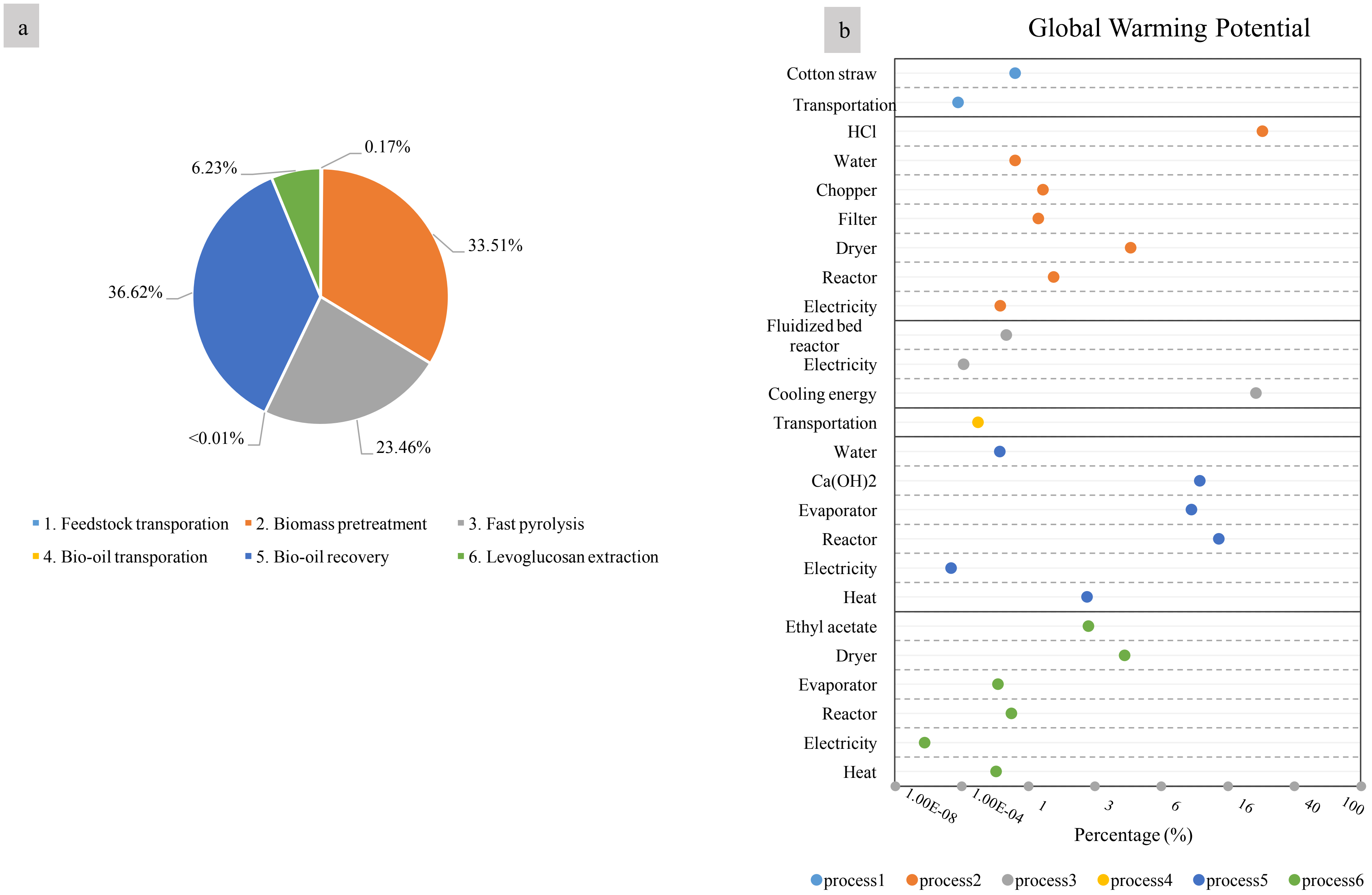


Figure 2. The percentage of different units (a) and different parameters (b) in resource depletion.



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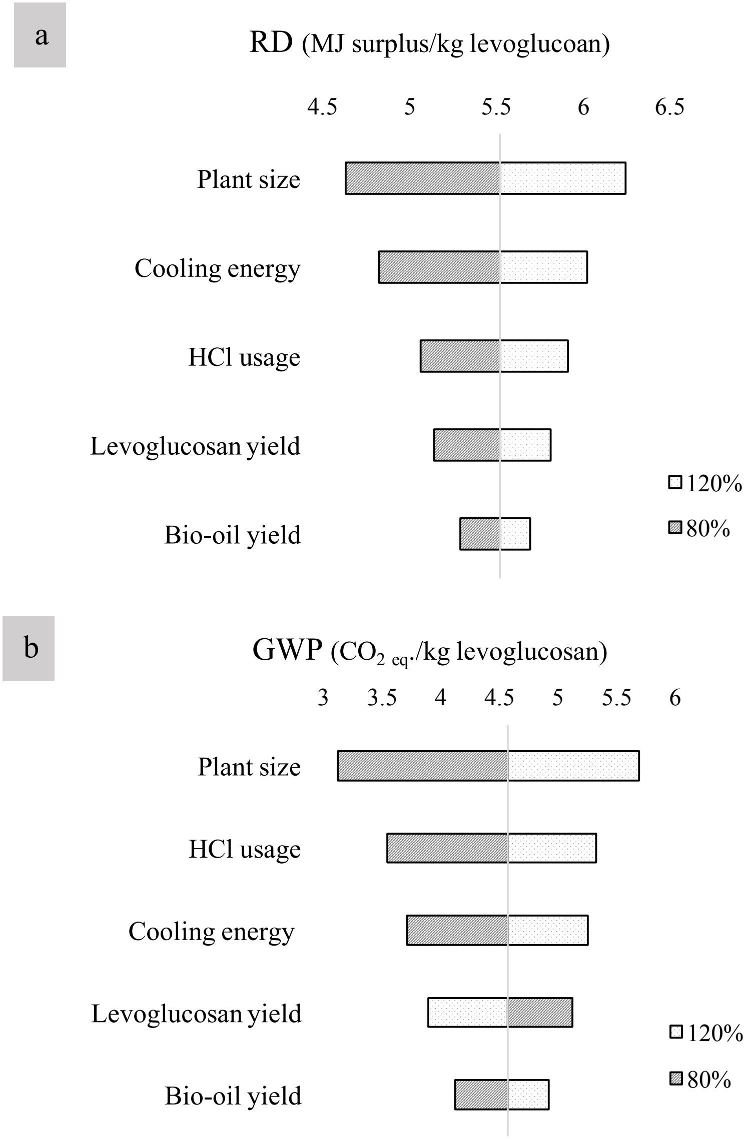

Figure 4 Sensitivity analysis of siginificant parameters for resource depletion (a) and global warming potential (b) of the bio-based levoglucosan production.

Table 1 The input data used for six processes in levoglucosan production

| Process | Input from technosphere | Unit | Input |
|---|---|---|---|
| Process 1 | Cotton straw | item | $2.01*10^{-3}$ |
| | The feedstock transport to pyrolysis plant | kg*km | $7.66*10^{-3}$ |
| Process 2 | Cotton straw (from process 1) | kg | 11.15 |
| | HCl | kg | $7.44*10^{-1}$ |
| | Water | kg | 2.85 |
| | [a] Chopping working hour | h | $5.94*10^{-6}$ |
| | [b] Filtration loading | item | $2.4*10^{-4}$ |
| | [c] Drying loading | $m^3$ | $2.6*10^{-4}$ |
| | [d] Reactor loading | item | $3.92*10^{-8}$ |
| | [e] Electricity | Wh | $8.59*10^{-1}$ |
| Process 3 | Acid cotton straw (from process 2) | kg | 10.29 |
| | [f] Fluidized bed reactor loading | item | $1.85*10^{-7}$ |
| | [e] Electricity | Wh | $5.55*10^{-3}$ |
| | [e] Cooling | kJ | $7.05*10^{3}$ |
| Process 4 | Bio-oil (from process 3) | kg | 7.21 |
| | The feedstock transport to refinery plant | kg*km | $1.24*10^{-1}$ |
| Process 5 | Bio-oil (from process 4) | kg | 7.21 |
| | Water | kg | 13.39 |
| | $Ca(OH)_2$ | kg | 12.66 |
| | $CO_2$ | kg | 10.76 |
| | [g] Evaporator loading | kg | 25.43 |
| | [d] Reactor loading | item | $3.85*10^{-7}$ |
| | [e] Electricity | Wh | $9.6*10^{-4}$ |
| | [e] Heat | kJ | $1.03*10^{3}$ |
| Process 6 | Raw levoglucosan (from process 5) | kg | 3.67 |
| | Ethyl acetate | kg | $4*10^{-2}$ |
| | [h] Drying loading | $m^3$ | $2.4*10^{-4}$ |
| | [g] Evaporator loading | kg | $4*10^{-2}$ |
| | [d] Reactor loading | item | $2.77*10^{-9}$ |
| | [e] Electricity | Wh | $2.49*10^{-5}$ |
| | [e] Heat | kJ | 5.53 |

[a] Chopper with an hourly output of 3.3 $m^3$/h and a life time output of 100000 $m^3$. The density of cotton straw is 200kg/$m^3$.

[b] Filter with a 50 $m^2$ of active surface per module.

[c] The function unit is kg water evaporated.

[d] Reactor with a storage capacity of 16000$m^3$ and a life time of 20 years.

[e] The data collection from the calculation of the equipment power and use time.

[f] The lifetime for the furnace is 20 years and with the operation time of 2100h/a.

[g] The lifetime of the evaporator is 20 years, and the functional unit is 1 kg water evaporated.

[h] The lifetime of the dryer is 20 years, and the functional unit is 1 kg water evaporated.

Table 2 The output data used for six processes in levoglucosan production

| Process | Output from technosphere | Unit | Output |
|---|---|---|---|
| Process 1 | Cotton straw | kg | 11.51 |
| Process 2 | Treated cotton straw | kg | 10.29 |
| | [a] Waste 1 | kg | 0.34 |
| | $H_2$ | kg | 0.66 |
| | $H_2O$ | kg | 3.45 |
| Process 3 | Bio-oil | kg | 7.21 |
| | Biochar | kg | 2.17 |
| Process 4 | Bio-oil | kg | 7.21 |
| Process 5 | Raw levoglucosan | kg | 3.67 |
| | $CaCO_3$ | kg | 9.99 |
| | Vapor | kg | 25.43 |
| | [b] Waste 2 | kg | 4.93 |
| Process 6 | Levoglucosan | kg | 1.00 |
| | [c] Waste 3 | kg | 2.67 |

[a] Waste 1 mainly includes chlorides.

[b] Waste 2 mainly includes $CaCO_3$, aromatic compounds and ester.

[c] Waste 3 mainly includes calcium salts, ester and water.

Table 3 LCA analysis for bio-based levoglucosan production from cotton straw

| Impact factor | Unit | Value |
|---|---|---|
| Acidification potential | kg $SO_2$ eq./kg levoglucosan | $1.91*10^{-2}$ |
| Ecotoxicity potential | CTUe/kg levoglucosan | 24.76 |
| Eutrophication potential | kg N eq./kg levoglucosan | $1.29*10^{-2}$ |
| Global warming potential | kg $CO_2$ eq./kg levoglucosan | 4.57 |
| Ozone depletion potential | kg CFC-11 eq./kg levoglucosan | $8.91*10^{-7}$ |
| Resource (fossil fuels) depletion | MJ surplus/kg levoglucosan | 5.52 |
| Human health-carcinogenic | CTUh | $5.76*E^{-07}$ |
| Human health-non-carcinogenic | CTUh | $9.46*E^{-07}$ |
| Photochemical ozone formation | kg $O_3$ eq./kg levoglucosan | 0.22 |
| Respiratory effects | kg PM2.5 eq./kg levoglucosan | $4.83*10^{-3}$ |

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