

# Environmental and economic impact of furfuralcohol production using corncob as a raw material

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Received: 3 October 2014 / Accepted: 14 January 2015 / Published online: 27 January 2015  
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## Abstract

**Purpose** Corncob as agricultural waste has dramatically increased in recent years. Some corncobs are recycled and reused as bioproducts, whereas a large amount remains unused and burned in the fields. Currently, furfural production technology is one of the most commonly used technologies for corncob valorization because furfural is one of the most promising chemicals for sustainable chemical production. However, very few studies have analyzed the impact of furfural and furfuralcohol production on the environment and economy via life cycle assessment (LCA) and life cycle costing (LCC). This study aims to quantify the environmental and economic impacts of furfural and furfuralcohol production, identify the main pollution processes and substances, improve potentials, and build a database on the furfural industry.

**Methods** Life cycle assessment and life cycle costing were carried out to estimate the environmental and economic impact of corncob-based furfural and furfuralcohol production.

**Results and discussion** The corncob production, transport, and electricity consumption stages had the greatest impact on the environment because of direct heavy metal, phosphate, and phosphorus emissions. The overall economic impact was mainly attributed to tax, corncob, transport, electricity, and

infrastructure investment. Optimizing corncob transport, raw materials and consumption efficiency, and waste disposal is highly important in reducing both environmental and economic burden.

**Conclusions** The key factors that contribute to reducing the overall environmental and economic impacts are increasing electricity consumption efficiency and furfural product yield, decreasing transport distance from corncob buyers to suppliers, choosing the appropriate corncob compression technology, and optimizing the wastewater reuse system.

**Keywords** Corncob · Furfural · Furfuralcohol · Life cycle assessment · Life cycle costing

## 1 Introduction

Worldwide corn production has dramatically increased because of significant population growth and industrialization. For instance, about  $5.92 \times 10^8$  and  $9.67 \times 10^8$  t of the total global corn production had been reported in 2000 and 2013, respectively (Cook 2014), corresponding to an increase of 63 % in just a span of 13 years. Thus, corncob as agricultural waste has likewise increased significantly. Some corncobs are recycled and reused as bioproducts (e.g., fertilizer, feed, bioethanol, activated carbon, xylose, xylooligomers, xylitol, and furfural), whereas a large amount remains unused and burned in the fields (Li et al. 2011), which may cause serious environmental problems. Most researchers have focused on developing energy and raw materials to enhance high-value valorization (Fan et al. 2013; Lei et al. 2014) which has considerable environmental impact and high nutritional content.

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Responsible editor: Seungdo Kim

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However, the inputs, outputs, and by-product of corn-cob-based production systems may cause increased environmental impacts and economic burden. Thus, methods for consistently evaluating environmental and economic impact are urgently needed.

Life cycle assessment (LCA) and life cycle costing (LCC) are effective approaches for evaluating the environmental and economic effects of a product, process, or activity, respectively. LCA and LCC are widely used in policy- and decision-making, marketing, consumer education, product design, and process improvement. In this study, LCA and LCC of corn-cob-based furfural and its most common product, furfuralcohol (Yan et al. 2014), were conducted because these products are important organic chemical raw materials that are widely used as chemical feedstock in such industries as casting, chemical, synthetic resin, medicine, pesticide, and petrochemical refining. Furfural is one of the most promising chemicals for sustainable chemical production (Bozell and Petersen 2010), with furfural production technology being one of the most commonly used technologies for corn-cob valorization (Yan et al. 2014). However, very few studies have analyzed the impact of furfural and furfuralcohol production on the environment and economy via LCA and LCC. Only one LCA study on furfural production has been reported in China on the basis of pilot-scale *experiment* data (Mao and Li 2010), and the said study failed to conduct LCA following ISO standards (2006a, b). The furfural industry is resource-, energy-, and pollution-intensive. Given the rising cost of electricity, raw materials, and labor, the industry requires a technological breakthrough to reduce raw material and energy consumption while increasing product yield. Additionally, the furfural industry emits numerous toxic compounds into the local environment. These compounds include particles, sulfuric acid, nitrogen oxide, and furfural, which are harmful to human health. This study aims to quantify the environmental and economic impacts of furfural and furfuralcohol production, identify the main pollution processes and substances, improve potentials, and build a database on the furfural industry.

## 2 Materials and methods

### 2.1 Functional unit

The functional unit is the production of 1 t of furfuralcohol. All raw materials and energy consumption, wastes, direct emissions, and transport are based on this functional unit.

### 2.2 System boundary

System boundary is set using a cradle-to-gate approach. This approach involves raw materials and energy production,

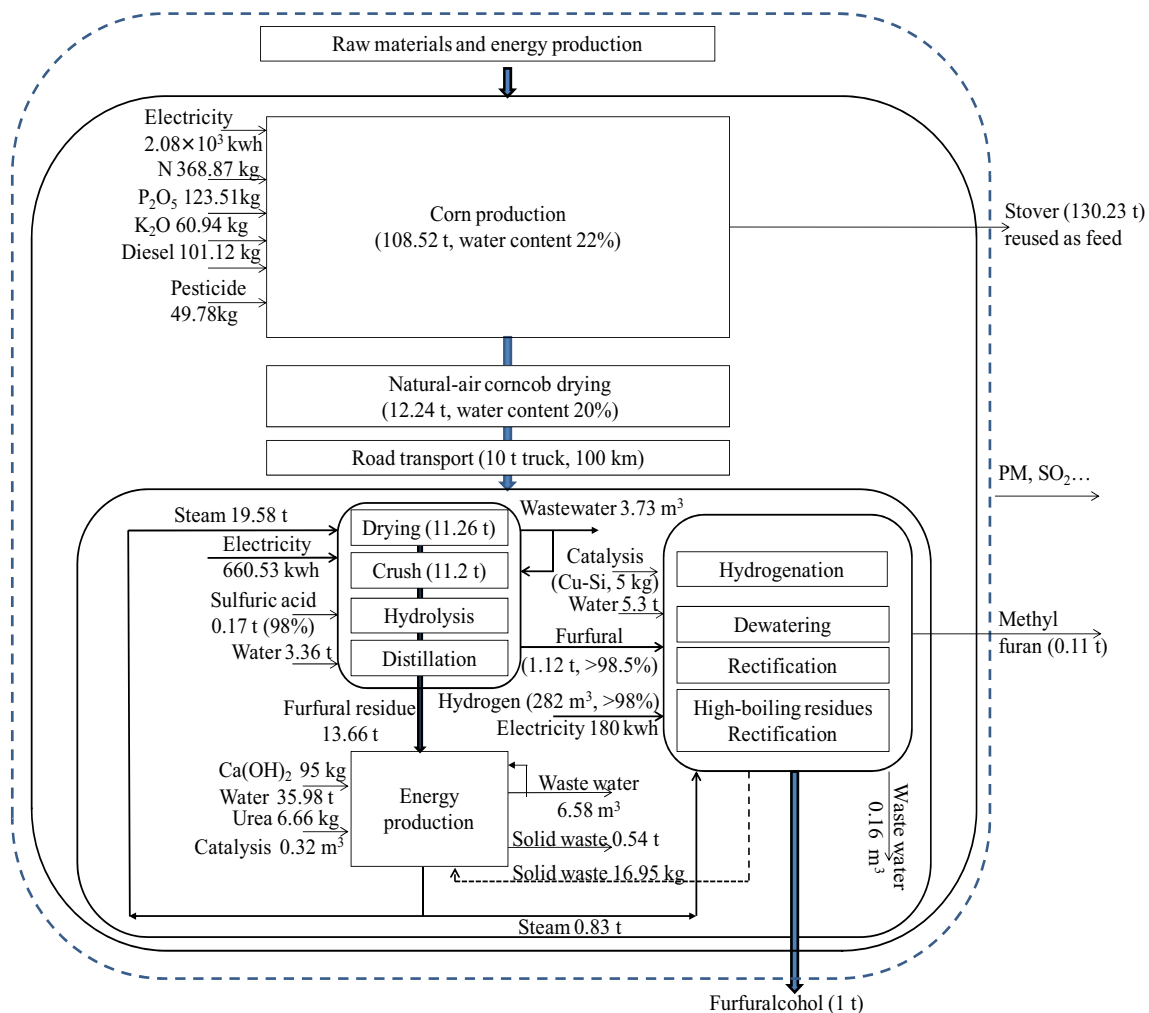
infrastructure, corn planting, corn-cob collection, furfural and furfuralcohol manufacturing, energy recovery from furfural residues, direct emissions, wastewater treatment on-site, as well as solid waste and wastewater reuse in furfuralcohol plants. Table 1 presents the characterization factor of the selected furfuralcohol production plant, whereas Fig. 1 presents the system boundary and mass flow. Mass allocation is performed relative to corn planting and furfuralcohol production. As shown in Fig. 1, during the corn production process, the final products are 108.52 t of corn, 130.23 t of stover, and 12.24 t of corn-cob. Mass allocation is performed to allocate inputs for corn planting among the three coproducts, i.e., 42.3 % to corn, 51.9 % to stover, and 4.88 % to corn-cob. Thus, all inputs for corn planting are multiplied by 0.048 and used as the inputs for 12.24 t corn-cob production. During the furfuralcohol production process, the final products are 1 t of furfuralcohol and 0.11 t of methylfuran. Therefore, mass allocation is performed relative to output products, with 90 % of inputs allocated to furfuralcohol production. Carbon dioxide emissions from corn-cob during furfuralcohol production processes are omitted from the inventory because corn-cob is a biogenic source. Coal-based electricity production, which serves an important function in the national electricity production of China (China Energy Statistic 2013), is also considered in this study.

### 2.3 Methodology

The life cycle impact assessment (LCIA) results are calculated at midpoint level using the ReCiPe method (Goedkoop et al. 2009; Schryver et al. 2009), which is one of the most recent indicator approaches available in LCA analysis. It contains 18 midpoint categories including climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, terrestrial

**Table 1** Characterization factor of a furfuralcohol production plant

Process	Unit	Amount
Water content		
Corn-cob	%	15
Furfural	%	≤0.2
Furfural residue	%	40
Furfuralcohol	%	≤0.3
Steam	MPa	1.2
Hydrogen content of hydrogen gas	%	≥98.5
Conversion rate of furfural	%	≥99
Dedust rate of bag-type dust collector	%	99
Desulfur rate	%	93
Denitrogen rate	%	80
Assumed lifetime of industry	Year	8



**Fig. 1** System boundary and mass flow

acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion. To compare the midpoint impact to each other and present the respective share of each midpoint impact to the overall environmental burden as well, normalization was applied in the present study. The normalized factor of midpoint impact was determined using the ratio of the impact per unit of emission divided by the per capita world impact for the year 2000 (Wegener Sleeswijk et al. 2008). Detailed information of the ReCiPe model is available on the website of the Institute of Environmental Science of Leiden University of the Netherlands ([http://www.cml.leiden.edu/research/industrialecology/research\\_projects/finished/recipe.html](http://www.cml.leiden.edu/research/industrialecology/research_projects/finished/recipe.html)).

Economic impact is assessed by using the LCC method, which is similar to LCA but considers economic impacts instead of environmental impacts (Hong et al. 2009, 2012). In this study, all the costs (i.e., production costs, taxes, labor fee,

capital investment, maintenance cost, interest, public welfare fund, and public reserve fund) arising from furfuralcohol production system were considered. The production costs of each life cycle stage in the system boundary include raw material buyer, electricity, transportation, and waste disposal costs. The costs of furfuralcohol consumption and end-of-life disposal are excluded because the system boundaries are set using a cradle-to-gate approach. Taxes involve income, urban construction, added value, and education taxes. Prices of raw materials, electricity, corncob, transport, and waste disposal based on current Chinese market prices and exchange rates on 21 August 2014 (USD 1.00=6.15 CNY) are used in the present study. For each life cycle stage, the life cycle inventory is listed and then simultaneously combined with LCA and LCC for cost-combined life cycle environmental assessment.

#### 2.4 Data sources

Life cycle inventory data on direct air pollutant emission, raw material and energy consumption, as well as waste discharge

were gathered from a furfuralcohol production site in Henan, China. The annual production capacity of the recently built site was approximately 60,000 t. Energy recovery data from furfural residue were taken from a different furfural production site in the same province because of the lack of detailed information on the same site. Data on coal-based electricity generation (Cui et al. 2012), corn production at a farm (Liu 2010), and road transport in China (Chen et al. 2014) were taken from the references. In addition, data on chemical production, infrastructure, and wastewater treatment were taken from Europe (Frischknecht et al. 2007) because these were not available in China. Table 2 illustrates the life cycle inventory, a data-based process of quantifying all inputs and outputs associated with each stage of production.

### 3 Results

#### 3.1 Life cycle impact assessment results

Table 3 shows the ReCiPe midpoint results and the contribution of the most significant processes. The electricity generation process had the greatest contribution in most categories except for ozone depletion, ionizing radiation, terrestrial ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, water depletion, and metal depletion categories, which were dominated by the direct air emission. Direct air emissions from diesel consumption during corn cob transport dominated most categories, except for freshwater and marine eutrophication, freshwater ecotoxicity, and agricultural land occupation, which were dominated by the corn cob production process because of direct water emission and arable land use. Similarly, direct air emissions from furfuralcohol and furfural residue reused for energy production had dominant contributions to photochemical oxidant formation, particulate matter formation, and terrestrial acidification. Calcium hydroxide process served an important function in the ozone depletion, whereas wastewater treatment had a dominant contribution to freshwater and marine eutrophication. Sulfuric acid production had a dominant contribution to particulate matter formation, terrestrial acidification, and water and metal depletion impacts. The potential impact of other processes (e.g., water, urea, infrastructure, hydrogen, solid waste disposal, fertilizer, pesticide) was negligible.

Figure 2 shows the normalized midpoint categories. Human toxicity, freshwater eutrophication, freshwater ecotoxicity, and marine ecotoxicity categories had dominant contribution to the overall environmental impact. Climate change, photochemical oxidant formation, particulate matter formation, ionizing radiation, terrestrial acidification, marine eutrophication, agricultural land occupation, metal depletion, and fossil depletion served a relatively minor function and were negligible in all other categories.

**Table 2** Life cycle inventory. Values are presented per functional unit (i.e., 1 t of furfuralcohol)

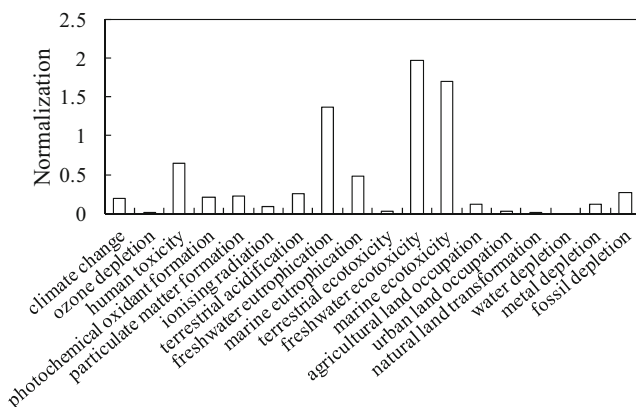
	Amount	Unit	Cost (\$)
Raw material			
Pesticide	2.43	kg	
Nitrogen fertilizer	17.99	kg	
Phosphate fertilizer	6.02	kg	
Potassic fertilizer	2.97	kg	
Sulfuric acid	0.17	t	13.82
Corn cob	12.24	t	398.05
Water	44.11	t	31.56
Selective catalytic reduction (SCR) catalysis	$3.0 \times 10^{-4}$	m <sup>3</sup>	0.73
Hydrogen gas	282	Nm <sup>3</sup>	20.28
Urea	6.66	kg	1.62
Calcium hydroxide	95	kg	15.45
Catalysis for furfuralcohol production	4.50	kg	32.93
Energy			
Electricity	914.28	kWh	90.83
Diesel	4.93	kg	6.12
Steam consumption for furfural production	19.58	t	350.21
Steam consumption for furfuralcohol production	0.75	t	13.41
Steam recovery from solid waste	-20.41	t	-365.06
Corn cob transport			
Diesel	68.74	kg	218.93
Land occupation			
Arable land occupation	$1.19 \times 10^4$	m <sup>2</sup>	
Industry land occupation	0.38	m <sup>2</sup>	
Building	0.04	m <sup>2</sup>	
Waste			
Wastewater	10.45	m <sup>3</sup>	2.38
Furfural residue	13.66	t	
Solid waste reused as building material	0.54	t	
Solid waste to landfill	15.27	kg	0.27
Sulfur dioxide	1.03	kg	
Particulates	1.09	kg	
Nitrogen oxides	1.55	kg	
Furfuralcohol	111.17	g	
Sulfuric acid	0.17	kg	
Methanol	165.67	g	
Furfural	73.33	g	
Acetic acid	52.67	g	
Labor			29.27
Construction investment			231.21
Interest			3.81
Maintenance			6.94
Public welfare fund and public reserve fund			15.91
Income tax, value-added tax, and other tax			335.86

**Table 3** Life cycle impact assessment midpoint results. Values are presented per functional unit

Category	Unit	Amount	Processes
Climate change	kg CO <sub>2</sub> eq	1.33 × 10 <sup>3</sup>	Electricity (52.8 %) + transport (24.8 %)
Ozone depletion	kg CFC-11 eq	4.03 × 10 <sup>-5</sup>	Transport (72.7 %) + calcium hydroxide (12.5 %)
Human toxicity	kg 1,4-DB eq	77.4	Electricity (44.3 %) + transport (35.1 %)
Photochemical oxidant formation	kg NMVOC	10.38	Direct emission (16.2 %) + electricity (47.8 %) + transport (26.4 %)
Particulate matter formation	kg PM10 eq	3.21	Direct emission (17.0 %) + electricity (34.4 %) + transport (26.1 %) + sulfuric acid (15.5 %)
Ionizing radiation	kg U235 eq	123.0	Transport (85.1 %)
Terrestrial acidification	kg SO <sub>2</sub> eq	9.52	Direct emission (19.3 %) + direct emission (19.9 %) + electricity (30.5 %) + transport (17.0 %) + sulfuric acid (24.1 %)
Freshwater eutrophication	kg P eq	0.17	Comcob (56.0 %) + electricity (15.3 %) + wastewater (17.6 %)
Marine eutrophication	kg N eq	4.31	Comcob (57.8 %) + electricity (14.2 %) + wastewater (15.0 %)
Terrestrial ecotoxicity	kg 1,4-DB eq	0.15	Comcob (75.4 %) + transport (14.5 %)
Freshwater ecotoxicity	kg 1,4-DB eq	8.36	Comcob (79.8 %) + electricity (8.8 %)
Marine ecotoxicity	kg 1,4-DB eq	2.24	Comcob (20.9 %) + electricity (31.8 %) + transport (31.9 %)
Agricultural land occupation	m <sup>2</sup> year	6.68 × 10 <sup>2</sup>	Comcob (98.5 %)
Urban land occupation	m <sup>2</sup> year	20.23	Transport (88.1 %)
Natural land transformation	m <sup>2</sup>	0.17	Transport (84.5 %)
Water depletion	m <sup>3</sup>	11.7	Transport (22.0 %) + sulfuric acid (72.4 %)
Metal depletion	kg Fe eq	52.99	Transport (70.8 %) + sulfuric acid (16.3 %)
Fossil depletion	kg oil eq	3.59 × 10 <sup>2</sup>	Transport (39.2 %) + electricity (49.7 %)

1,4-DB 1,4-dichlorobenzene; NMVOC non-methane volatile organic compounds

The substances that contributed the most to human toxicity were mercury, lead, arsenic, selenium, and vanadium (Fig. 3). Phosphate and phosphorus emissions were the dominant contributors to the freshwater eutrophication score. Zinc, nickel, vanadium, and phosphorous emission to water dominated the freshwater ecotoxicity category, whereas beryllium, zinc, phosphorus, nickel, vanadium released to water, and copper released to air dominated marine ecotoxicity. The dominant substances were mainly generated from energy (diesel and electricity) consumption during the corn cob and furfural production and transport stages. Fertilizer consumption for corn planting was also dominant in terms of phosphate and phosphorus emissions. Accordingly, although chemical,

**Fig. 2** Normalized midpoint scores for the full life cycle

infrastructure, and wastewater treatment data from Europe (Frischknecht et al. 2007) were used in this study, their LCIA effects were insignificant.

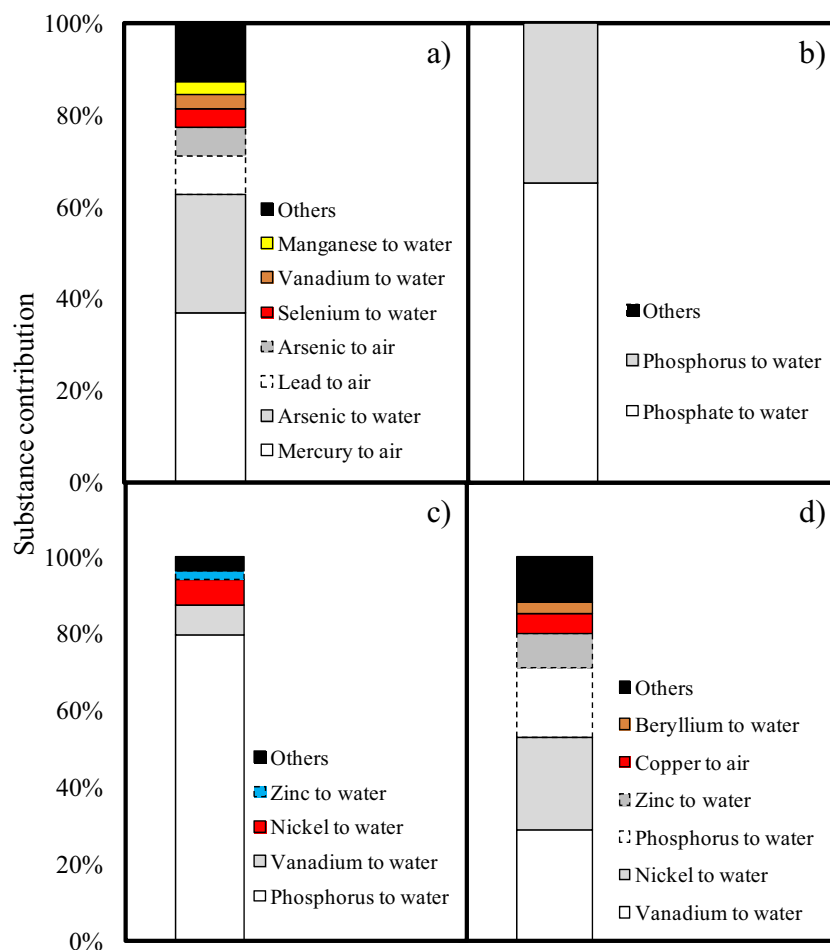
### 3.2 Life cycle costing

Figure 4a shows the economic assessment results. The total economic impact is \$1454.5/t, which can largely be attributed to the cost of tax, corn cob, infrastructure, corn cob transport, and electricity. Water, labor, and hydrogen had relatively minor economic impacts and were negligible for all other substances (e.g., sulfuric acid, solid waste disposal, wastewater treatment, calcium hydroxide, and urea). Figure 4b demonstrates the cost-coupled LCA analysis, in which a normalized LCIA environmental value is selected to indicate environmental impacts. Corn cob production imposes the highest environmental and economic burden because of the direct water emission generated from fertilizer consumption and corn cob buyer price, respectively. By contrast, furfural alcohol production had the lowest environmental and economic impact. Tax, infrastructure fee, and labor cost also had significant economic impact.

### 3.3 Corn cob compression

As shown in Fig. 4, corn cob transport had a relatively important contribution to the overall environmental and economic impact because of the low density of corn cob (0.21 t/m<sup>3</sup>),

**Fig. 3** Contribution of processes to the key categories: **a** human toxicity, **b** freshwater eutrophication, **c** freshwater ecotoxicity, and **d** marine ecotoxicity



which caused increased diesel consumption during road transport. Corncob compression technology was recently used to increase transport efficiency. However, additional electricity consumption (around 8.3 kWh/t) is needed during corn cob compression. Such requirement may cause more environmental problems. Thus, corn cob transport with and without compression technology is estimated in Fig. 5. Results showed that corn cob with compression technology provided higher environmental benefit than that without compression in all categories. Overall environmental and economic furfural alcohol burdens can approximately be reduced by 3.7 and 1.5 %, respectively.

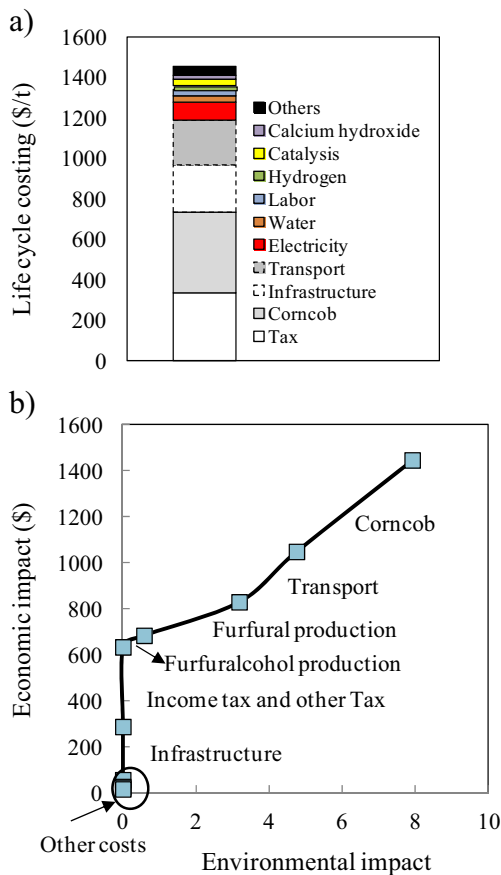
### 3.4 Sensitivity analysis

Table 4 shows the results of the sensitivity analysis of the main contributors to a 5 % variation in inputs/outputs, which was conducted to identify the major influence on the LCIA and LCC results obtained from the present research. The comparison of the LCIA results indicates that a 5 % variation in corn cob consumption for furfural alcohol production would lead to a variability of 18.86 kg CO<sub>2</sub> eq, 1.45 kg 1,4-dichlorobenzene (1,4-DB) eq, and 0.14 kg non-methane volatile organic

compounds (NMVOC) on climate change, human toxicity, and photochemical oxidant formation, respectively. For the other categories and main contributors, a similar analogy can be made with the sensitivity results shown in Table 4. A 5 % variation in corn cob consumption had the highest variability in all categories except for climate change, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial acidification, and fossil depletion, in which electricity consumption produced the highest variability. By contrast, the variation of wastewater had the lowest variability in all categories except for ionizing radiation, marine and freshwater eutrophication, and metal depletion, in which electricity consumption efficiency also had the lowest variability.

## 4 Discussion

Although furfural is considered a value-added product (Yan et al. 2014) and is a promising component of sustainable production of fuel and chemicals (Bozell and Petersen 2010), its world production has shifted from developed countries (e.g., Europe and Japan) to developing countries (e.g., China and Dominican Republic) over the last decade (Marcotullio 2011).



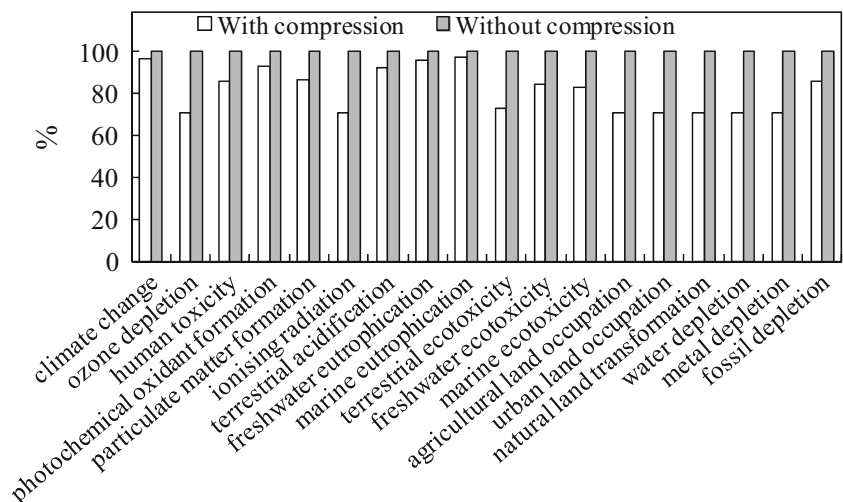
**Fig. 4** Economic assessment results: **a** contributions of the most significant substance to the overall cost and **b** cost-combined LCIA result

The shift is mainly attributed to the environment-, resource-, and labor-intensive properties of furfural manufacturing. China is the largest producer of both furfural and furfuralcohol in the world (RIRDC 2006; Jong and Marcotullio 2010). These products are mainly produced from agricultural corn-cob waste. However, the Chinese furfural industry suffers

from low product yield, high raw material consumption, and low energy efficiency. Most of the furfural produced in China has low yield (30 to 35 % of theoretical) and high energy consumption (around 600 kWh/t furfural). The furfural yield in this study was 45 %, significantly lower than the reported advanced furfural production technology (furfural yield of 55 %) (RIRDC 2006). If advanced furfural yield (55 %, RIRDC 2006) is considered, then the overall environmental impact for 1 t of furfural and furfuralcohol production will decrease by approximately 13.1 and 11.0 %, respectively, whereas the overall cost will decrease by 5 %. Additionally, the approximate use of 200 kWh of electricity is higher than that reported in the RIRDC reference (RIRDC 2006). If the advanced electricity consumption level (400 kWh/t furfural, RIRDC 2006) is considered, then the overall environmental impact for 1 t furfural and furfuralcohol production will further decrease by approximately 6.7 and 5.4 %, respectively. Several new technologies for furfural production have been developed through laboratory experiments. These technologies achieved nearly 75 % increased yield (Bhaumik and Laxmikant Dhepe 2014; Rong et al. 2012; Tao et al. 2011), indicating a significant potential for environmental and economic improvements.

World furfural prices largely fluctuate depending on the Chinese production market (Jong and Marcotullio 2010). Figure 4 shows the total cost for furfuralcohol production in the sample company at \$1454.5/t, which is lower than the current market price (\$1545/t). The processes that contributed most to the total cost were corn cob market price and transport cost. Results are consistent with those of a previous reported study (Jong and Marcotullio 2010) that showed that the cost of biomass materials largely affected the economic impact of furfural production. When furfural yield is at 45 and 55 %, the theoretical upper-bound road transport distances should be approximately 300 and 450 km, respectively, whereas the theoretical upper-bound corn cob buyer price will be around \$40/t

**Fig. 5** Effect of corn cob compression on LCIA midpoint results



**Table 4** Sensitivity of main contributors to a 5 % variation in inputs/outputs. Values are presented per functional unit

	Unit	Corn cob	Electricity	Transport distance	Sulfuric acid	Wastewater
Variation	%	5	5	5	5	5
Climate change	kg CO <sub>2</sub> eq	18.86	35.24	16.52	1.27	0.21
Human toxicity	kg 1,4-DB eq	1.45	1.71	1.36	0.25	0.10
Photochemical oxidant formation	kg NMVOC	0.14	0.25	0.14	0.02	9.47 × 10 <sup>-4</sup>
Particulate matter formation	kg PM10 eq	4.63 × 10 <sup>-2</sup>	5.52 × 10 <sup>-2</sup>	4.19 × 10 <sup>-2</sup>	2.49 × 10 <sup>-2</sup>	5.65 × 10 <sup>-4</sup>
Ionizing radiation	kg U235 eq	5.31	0.13	5.23	0.23	0.10
Terrestrial acidification	kg SO <sub>2</sub> eq	0.10	0.14	0.08	0.11	1.70 × 10 <sup>-3</sup>
Freshwater eutrophication	kg P eq	5.49 × 10 <sup>-3</sup>	1.32 × 10 <sup>-3</sup>	6.44 × 10 <sup>-4</sup>	9.12 × 10 <sup>-5</sup>	1.52 × 10 <sup>-3</sup>
Marine eutrophication	kg N eq	0.14	0.03	0.01	1.21 × 10 <sup>-3</sup>	0.03
Freshwater ecotoxicity	kg 1,4-DB eq	0.37	3.66 × 10 <sup>-2</sup>	3.26 × 10 <sup>-2</sup>	5.54 × 10 <sup>-3</sup>	2.41 × 10 <sup>-3</sup>
Marine ecotoxicity	kg 1,4-DB eq	5.91 × 10 <sup>-2</sup>	3.56 × 10 <sup>-2</sup>	3.56 × 10 <sup>-2</sup>	7.34 × 10 <sup>-3</sup>	2.46 × 10 <sup>-3</sup>
Agricultural land occupation	m <sup>2</sup> year	33.07	4.49 × 10 <sup>-3</sup>	0.15	0.06	2.55 × 10 <sup>-3</sup>
Metal depletion	kg Fe eq	1.94	0.05	1.87	0.43	0.06
Fossil depletion	kg oil eq	7.41	8.92	7.03	0.40	0.04
LCC	\$/t	30.85	4.09	3.93	0.69	0.12

and \$49/t, respectively. If the distance from the local corn cob storage to the furfuralcohol production site is over this distance, total cost will exceed the aforementioned market prices, proving that high furfural yield has major effects on the viability of furfural industries.

Lei et al. (2014) reported that the total production cost of corn cob-based ethanol production in China is approximately \$736/t ethanol, which is lower than current market prices (\$1024/t ethanol). This finding indicates that the corn cob-based ethanol production may be a good valorization pathway for corn cob disposal. Thus, comparative analysis of corn cob utilization technologies to optimize corn cob-to-bioproduction pathways is significantly needed in the near future.

## 5 Conclusions

Improvements to the life cycle environmental and economic performance of furfuralcohol production were evaluated in this work. Results indicated a significant potential for environmental and economic improvements in the furfuralcohol industry by increasing furfural yield, optimizing wastewater and electricity consumption efficiencies, and decreasing corn cob transport distance. Research results will help expand the life cycle inventory database, provide useful scientific information for identifying regional best practices for corn cob valorization, and rectify problems in corn cob-based furfural and furfuralcohol production. However, given the limitations associated with the currently available data, a more holistic and reliable sustainability assessment, along with uncertainty analysis, social information, and governmental policies, should be conducted in the future. Additionally, biogenic carbon dioxide emissions from furfuralcohol production processes are

omitted in this study because of the complexities of accurate climate accounting of industrial agricultural systems. Soil carbon, indirect land use change, and biodiversity are important aspects that have recently received attention in LCA of biomass. Further research on these areas is necessary to systematically assess the furfuralcohol production technology.

**Acknowledgments** We gratefully acknowledge the financial support from the National Natural Science Foundation of China (grant no. 41101554); SRF for ROCS, SEM (grant no. 2011-1568); and the National High-Tech R&D Program of China (863 Program, grant no. 2012AA061705).

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