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An economic and environmental evaluation for bamboo-derived bioethanol

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The potential for bioethanol from bamboo using three different pretreatment technologies (Liquid hot water (LHW), dilute acid (DA) and soaking in aqueous ammonia (SAA)) is assessed via techno-economic and environmental analyses. The minimum ethanol selling price (MESP) is used to compare the economic potential of the pretreatment processes, and these are 0.554, 0.484 and 1.014 $/litre for DA, LHW and SAA pretreatments, respectively. The bioethanol pump price under current and future policy scenarios in China is compared with petrol and reveals that bioethanol produced via DA and LHW pretreatments could be economically competitive even without government support. From an environmental perspective, a life cycle assessment approach is used to evaluate bamboo-derived bioethanol for full environmental impact categories, and this is compared with petrol on a 'well-to-wheel' basis. It was found that all three bioethanol pathways would be environmentally better than petrol with greenhouse gas (GHG) emissions reduced by 45-93%. A comparison of bamboo-based bioethanol with other cellulosic feedstocks not only suggests that bamboo could be a viable and competitive feedstock for bioethanol production, but also demonstrates that amongst the pretreatment technologies tested, LHW has the most potential for achieving favourable economic and environmental outcomes.

Abbreviations

AD	Anaerobic digestion	HTP	Human toxicity potential
ADP	Abiotic resources depletion potential	HPLC	High-performance liquid chromatography
AFEX	Ammonia fibre expansion	LCA	Life cycle assessment
AP	Acidification potential	LCIA	Life cycle impact assessment
CHP	Combined heat and power	LHW	Liquid hot water
CFC^{-11}	Trichlorofluoromethane	MESP	Minimum ethanol selling price
COD	Chemical oxygen demand	NREL	National Renewable Energy Laboratory
DA	Dilute acid	ODP	Ozone layer depletion potential
DB	Dichlorobenzene	POCP	Photochemical-oxidants creation potential
EP	Eutrophication potential	SAA	Soaking in aqueous ammonia
FAETP	Freshwater aquatic ecotoxicity potential	SE	Steam explosion
FFV	Flexible-fuel vehicle	TEP	Terrestrial ecotoxicity potential
FPU	Filter paper unit	WWT	Wastewater treatment
GWP_{100}	Global warming potential (100 year horizon)	VOC	Volatile organic compounds
GHG	Greenhouse gas		

1 Introduction

Biofuels produced from renewable resources such as lignocellulosic biomass can enhance energy security and reduce fossil fuel consumption in the transport sector, helping mitigate climate change [1]. Many governments have recognized their potential and are setting up mandates (*e.g.* the Renewable Fuel Standard in the US and the Renewable Energy Directive in the

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EU) to enhance production and consumption [2]. As a result, global biofuel production reached 100 billion litres in 2010 and provides about 3% of the total road transport fuel on an energy basis [3]. Bamboo is potentially a promising feedstock for advanced bioethanol production due to features such as its rapid growth, perennial nature, tolerance to extreme climatic conditions and low management requirements. Globally, Asia has the richest bamboo resources, accounting for 65% of global bamboo resources. The major bamboo producing countries include India (11.4 million ha bamboo forests), China (5.4 million ha), and Indonesia (2 million ha). This is followed by America, which holds 28% of global bamboo forests, led by countries such as Brazil and Chile [4]. Bamboo has played a significant role throughout human history in applications ranging from food to construction, however only more recently has its value in the field of bioenergy been proposed [5].

Bamboo's cell wall is comprised of the polymeric constituents cellulose, hemicellulose and lignin. However, the complex physical and chemical interactions that exist between these components requires a pretreatment stage to maximise the enzymatic hydrolysis of cell wall sugars into their monomeric form prior to fermentation into ethanol [6-8]. Various mechanical, chemical, and physical pretreatment technologies have been studied and are found to effectively disrupt the biomass cell wall structure, increase accessible cellulose surface area via solubilising lignin and/or hemicellulose and reduce cellulose crystallinity [9]. As a novel feedstock for bioethanol production, bamboo has not been widely studied in the field of bioenergy. Sun *et al.* (2011) [10] reported the bioethanol production from bamboo via concentred acid hydrolysis whilst Wang *et al.* (2011) [11] documented a bioethanol yield of 170 litres per ton from bamboo via bioconversion after steam explosion pretreatment. Our previous study revealed an ethanol production potential from 147 to 198 million litres per year from bamboo via liquid hot water (LHW) pretreatment followed by enzymatic hydrolysis. It also evaluated the economic viability of this technology and reported an ethanol production cost at 0.484 \$/litre [12]. In addition to LHW, two other potential pretreatments, dilute acid (DA) and soaking in aqueous ammonia (SAA), were also selected for comparison purposes in this study. Experimental data and process simulation modelling was used to generate techno-economic and environmental profiles for these three ethanol production pathways. These aspects of bamboo-derived bioethanol were then compared with conventional gasoline and against bioethanol from other biomass.

2 Material and Methods

2.1 Experimental design

The raw (unpretreated) bamboo material has a moisture content of approximately 10% and a total sugar content of 64.2% of dry matter (DM) including 38.4% glucan, 20.5% xylan, 3.6% galactan and 1.8% arabinan. Lignin, extractives and ash comprised 20.8%, 13.5% and 0.9% of DM, respectively [12]. Bamboo culms were chopped, milled and sieved to collect material between a particle size of 850 and 180μm. LHW pretreatment was carried out using a Dionex Accelerated Solvent Extractor (ASE) 200 machine at 190°C for 10 minutes with water. In SAA pretreatment, biomass was soaked with 15% NH_4OH in pressure tubes which were placed in a temperature-controlled oven at 100°C for 24 hours. The DA pretreatment was also performed in the ASE 200 with 0.2% sulphuric acid at 160°C for 15 minutes. For these pretreatments, a wide range of conditions were initially tested, and these were narrowed down to those reported in this study based on the criteria of maximising sugar release. Following these pretreatments, the slurry was separated into two parts: the supernatant liquid was collected for compositional analysis by high performance liquid chromatography (HPLC) whereas the solid fraction was washed to prepare for enzymatic hydrolysis. A commercial enzyme cocktail Cellic® Ctec 2 from Novozymes A/S Demark was applied at 10 FPU/g glucan for a 72 hour incubation at 50°C [12].

2.2 Process simulation

The experimental results from pretreatment and enzymatic hydrolysis together with assumptions were used to construct the process simulations in AspenPlus™. The process design for ethanol production pathways via three various pretreatments were adapted from the NREL corn stover-to-ethanol model [13], and is designed to process 2000 dry tonnes of bamboo per day, operating at 8410 hours per year. Fig. 1 shows the schematic diagram for bamboo-to-ethanol process.

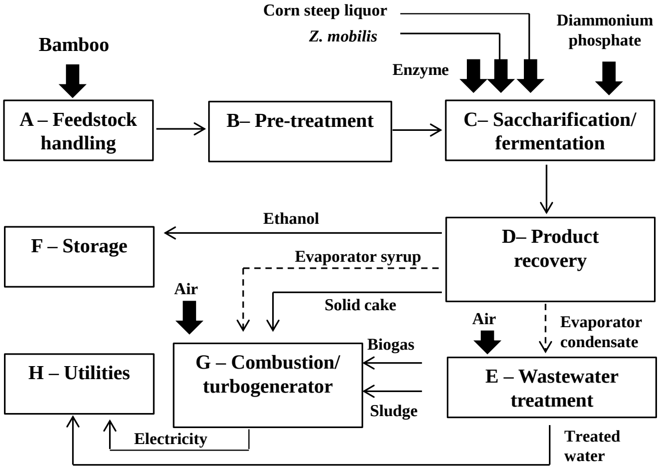

Fig.1 Scheme diagram of the bamboo ethanol production process [12] (streams shown in dashed lines vary in cases depending on different pretreatments)

Bamboo is unloaded, washed and milled to a suitable particle size in Section A. It is then transferred to the pretreatment area (Section B) where LHW, SAA or DA pretreatments are applied at a total solids loading of 30% (w/w) [13]. Pretreated bamboo is then sent to separate enzymatic hydrolysis and fermentation (Section C) where the polysaccharides are hydrolysed to monomeric sugars which are then fermented into ethanol by recombinant microorganism *Zymomonas mobilis* which co-

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ferments glucose and xylose [13]. The experimental yields for sugar and by-products as results of sugar degradation in pretreatment and enzymatic hydrolysis are listed in Table 1. The sugar conversion efficiencies for glucose and xylose in fermentation are adopted from the NREL model as 95% and 85%, respectively, whilst 3% of monomeric sugars are assumed to convert to contamination products such as glycerol, succinic acid and xylitol [13]. The operation conditions and nutrient loading in enzymatic hydrolysis and fermentation are adopted from the NREL model [13]. The fermentation liquor is then concentrated to 99.6% *via* distillation and molecular sieve adsorption (Section D). The distillation bottoms are condensed into a syrup using evaporators in LHW pretreatment, which is sent to the combustor (Section G). Whereas in DA and SAA pretreatments, liquids are separated from solids and sent to wastewater treatment (WWT) (Section E), which includes anaerobic digestion (AD) and aerobic digestion. The biogas yield and chemical oxygen demand (COD) removal efficiencies are adopted from the NREL model [13]. Treated water is then recycled as process water within the plant. For DA and SAA pretreatments, ammonia is used both to neutralise sulphuric acid and as a treatment reagent, and is converted to nitrate in aerobic digestion. The formation of nitric acid lowers the pH, resulting in the requirement for caustic to re-neutralise the pH. The syrup from Section D combined with the biogas and cell mass (sludge) from Section E are sent to combined heat and power (CHP) in Section G for steam and electricity generation, which also supplies the energy demand of the process. The surplus electricity is sold to the National Grid as a co-product. For DA pretreatment, the level of sulphur in the flue gas requires additional flue gas desulphurization and lime is sprayed into the flue gas converting 92% of the SO_2 into calcium sulphate.

Table 1 Sugar and by-products yields in pretreatment and enzymatic hydrolysis [14]

	DA	LHW	SAA
Pretreatment conditions	0.2% H_2SO_4 at 160°C for 15 minutes	190°C for 10 minutes	15% NH_4OH at 100°C for 24 hours
Pretreatment efficiencies (% of reactants)	Glucan, 32.5% Xylan, 84.2% Lignin, 5.0%	Glucan, 15.0% Xylan, 83.6% Galactan, 83.4%	Glucan, 7.9% Xylan, 13.7% Galactan, 73.7% Lignin 30.5%
Enzymatic hydrolysis efficiencies (% of remaining reactants)	Glucan, 36.5% Xylan, 21.9%	Glucan, 26.3% Xylan, 41.3% Galactan, 26.3%	Glucan and galactan, 22.7% Xylan and arabinan, 46.1%

2.3 Techno-economic analysis

The obtained mass and energy balance from AspenPlus™ process simulation are used for the techno-economic analysis. The capital costs are estimated by scaling up or down the purchased equipment from NREL's vendor quotations [13]. All costs in this study are indexed to the reference year of 2011. As one of the main bamboo producing-countries worldwide, China is selected as the country for this analysis. Cost parameters used in this analysis are listed in Table 2. Fixed costs including labour and overhead are adopted from the NREL model. A discounted cash flow method was applied to calculate the minimum ethanol selling price (MESP), which is the bioethanol price determined using a discounted rate of 10% where the net present value of the project is zero. The other financial assumptions applied in the techno-economic analysis are adopted from our previous study [12].

Table 2 Summary of techno-economic cost parameters

Materials/chemicals/	Price ($/tonne or indicated)	Reference
Bamboo	44.6	15
Corn steep liquor	57.9	13
Diammonium phosphate	502.5	16
Enzyme	507.0	17
Sorbitol	1148	13
Sulphuric acid	97.5	18
Ammonia	445.6	19
Lime	120	20
Caustic	317.5	21
Fresh water	0.3	13
Boiler feed water chemicals	5092	13
Cooling tower chemicals	3637	13
Transport cost	0.05 ($/km)	22
Landfill tax	4.5	23
Electricity credit	0.11 ($/kwh)	24
Income tax	25%	25

2.4 Life cycle assessment (LCA)

LCA is a method assessing the environmental impacts of a product through its life cycle and was conducted with regard to ISO standards [26]. Life cycle impact assessment (LCIA) was performed using model CML baseline 2000 v2.5 incorporated in software Simapro v7.3 [27]. The impact categories considered are Abiotic resources Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (100 year horizon) (GWP_{100}), Ozone layer Depletion Potential (ODP), Human Toxicity Potential (HTP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Terrestrial Ecotoxicity Potential (TEP) and Photochemical-Oxidants Creation Potential (POCP).

The LCA in the present study aims to (1) assess the environmental profile of bioethanol produced from bamboo using different pretreatment technologies, and (2) compare these bioethanol pathways with conventional petrol. Accordingly, the functional unit is defined as (1) '*1kg ethanol produced from bamboo*', and (2) '*1km travelled in a Flexible-fuel vehicle (FFV)*'. The life cycle of bamboo-derived ethanol includes bamboo plantation and harvesting, transport, ethanol production, ethanol distribution and end use in a FFV. In addition to literature reviews, mass and energy balance data for

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bioethanol production were obtained from the AspenPlus™ model. The inventory data of bamboo plantation and harvesting (Table 3) are derived from van der Lugt *et al.* (2003) [28] and the assumptions about transportation are listed in Table 4. The life time of bamboo is 20 years with the culms productivity of 48 dry ton/ha per year [28].

Table 3 Inventory data for bamboo plantation and harvest [28]

Plantation inputs	**Application year**	**Application amount**	**Harvest activities**	**Machine needed**	**Fuel consumption**
NPK (10-30-10) (kg/ha)	1	90	Sawing culms	Chainsaw	1.08 litre gasoline/ tonne culms (dry)
Nitrate (kg/ha)	1-2-3	90-90-90	Branch removal	Chopping knives	-
Boron (Solubor or Menoral 8) (kg/ha)	2-3-4-5	135-180-360-360	Preservation	Air-pump	66.7 kWh/tonne culms (dry)
Herbicide (litre/ha)	1	2	Drying	Air-dry	-

Table 4 Assumptions about transportation

Activities	**Vehicle mode**	**Fuel type**	**Distance**
On-site plantation – preservation/dry	Truck 4.5 ton	Diesel	2 km [28]
Fertilizers, herbicides and chemicals from wholesalers to farm or to ethanol plant	Lorry 28 ton	Diesel	500 km
Bamboo culms from farm to ethanol plant	Lorry 16 ton	Diesel	100 km
Enzyme from wholesaler to ethanol plant	Rail/ Lorry 20 -28 ton		100km / 1150 km
Chemicals from wholesalers to ethanol plant	Rail/ Lorry 20-28 ton		100km/ 150 km

The inventory for most inputs such as chemicals, fertilisers, energy and infrastructure is from the Ecoinvent database v2.2 [29]. Inventories for outputs in the bamboo cultivation process such as emission factors for field emission and fuel combustion in the chainsaw engine are derived from the IPCC approach [30] and the EPA report [31]. The inventory data for enzyme (Cellic Ctec) production are provided by Novozymes A/S Denmark [32]. Outputs in the bioethanol production process such as emissions to air occurring in fermentation (95% of CO_2 and 0.3% of ethanol [13]) and WWT (3% of biogas [13]) are obtained from the process simulation. Emissions from combustion are estimated based on the feed stream and the emission factors adopted from studies using woody biomass as a fuel [33-36]. These are 0.036 kg/GJ for PM10, 0.104 kg/GJ for NOx, 0.0153 kg/GJ for CO, 0.00215 kg/GJ for VOC (volatile organic compounds) and 0.007 kg/GJ for N_2O. All S from the feedstock and sulphuric acid is assumed to be converted to SO_2 in combustion among which 1% becomes sulphuric acid [13].

The allocation method 'system expansion' was applied on surplus electricity which is credited with avoided emissions from generation of an equivalent amount of the average National Grid electricity.

3 Results and discussion

3.1 Techno-economic analysis results

Three pretreatment processes (DA, LHW and SAA) are evaluated based on their MESP, ethanol production rate, bioethanol yield and surplus electricity generation (Table 5). At the same level of enzyme loading (10 FPU/g glucan), DA pretreatment results in the highest ethanol production rate and ethanol yield at 179 million litres/year and 234 litres/ton bamboo, respectively. At the lowest end of the scale, SAA delivers an ethanol production rate of 95 million litres/year and yield of 125 litres/ton. This pattern was reversed for electricity generation, with DA pretreatment generating 43.9 MW of electricity compared to LHW pretreatment at 54.4 MW and SAA pretreatment at 57.5 MW, due to the lower amount of sugars fermented in these two processes, thus available for combustion.

Table 5 Simulation results for three bioethanol production pathways

Pretreatment	MESP ($/litre)	Bioethanol production (MMl/year)	Bioethanol yield (litres/ton)	Electricity generation (MW)
DA	0.547	179	234	43.9
LHW	0.484	147	192	54.4
SAA	1.014	95	125	57.5

The lowest MESP is found for ethanol production using LHW pretreatment due to its minimal raw material cost compared with other two pretreatments (Fig. 2). Despite DA yielding the highest ethanol production, it is not the most economically favourable due to the cost of pretreatment, specifically from purchase of sulphuric acid and ammonia, which negates the profits achieved from the higher bioethanol yield. The MESP breakdown for the three pretreatment processes is shown in Fig. 2. The capital cost is the biggest contributor accounting for 54%-69% of production cost. Bamboo cost is the second biggest contributor (36%-51%) followed by the cost of other raw materials including enzyme.

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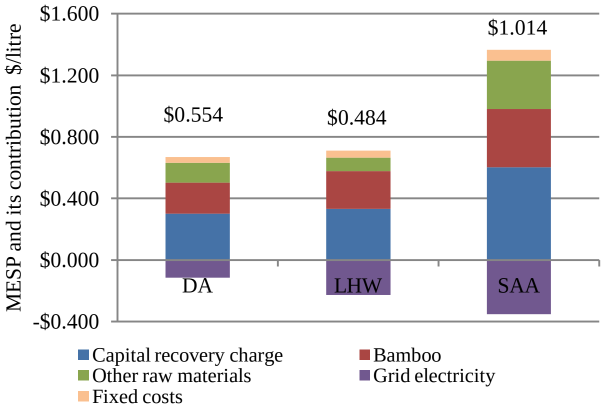

Fig. 2 Cost breakdown of bamboo bioethanol from three pretreatment processes. MESPs in $/litre listed above the bar.

In order to assess whether bamboo-derived bioethanol could be competitive with petrol in China, a theoretical bioethanol price at the pump was calculated to include the fuel production cost (MESP), a distribution cost (0.032 $/litre [37]), value-added tax (17% [38]) and a fuel excise tax (5% [38]). Based on the reference year of 2011, it is assumed that the Chinese government would provide support for biofuels in various forms. Fuel ethanol producers, blenders and gasohol (fuel blend of ethanol and petrol) retailers are exempted from the national consumption tax and VAT; and designated producers can also receive a subsidy of 0.16 $/litre bioethanol. Originally a subsidy of 0.20 $/litre in 2008, this amount has been progressively reduced each year, [38] and is expected to be diminished in future years.

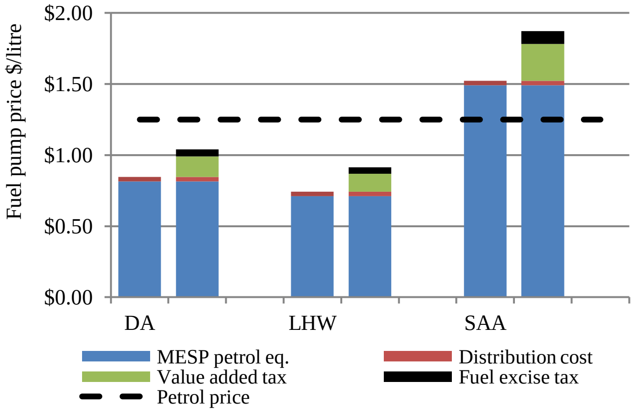

Fig. 3 Fuel pump price comparison of bamboo bioethanol using three pretreatment processes with petrol in China. Left columns represent current scenarios and right columns future scenarios.

In Fig. 3, the pump price of bamboo-derived ethanol is compared with petrol (1.25 $/litre as an average price over 2011). This is first modelled under the current bioethanol policy scenario, which includes exemption of tax and subsidy provision, and is also modelled in the future scenario without these government support measures. The bioethanol prices have been adjusted to their petrol equivalent for comparison based on the ratio of ethanol to petrol energy content (0.68[37]). Fig. 3 shows that the cost of bamboo bioethanol produced using DA and LHW pretreatments is substantially lower than that of petrol in 2011, and could therefore be economically competitive with petrol in both current and future scenarios modelled. Whereas the cost of bioethanol produced via SAA pretreatment was uneconomical already in the current scenario and this lack of competitiveness was therefore exaggerated in the future scenario.

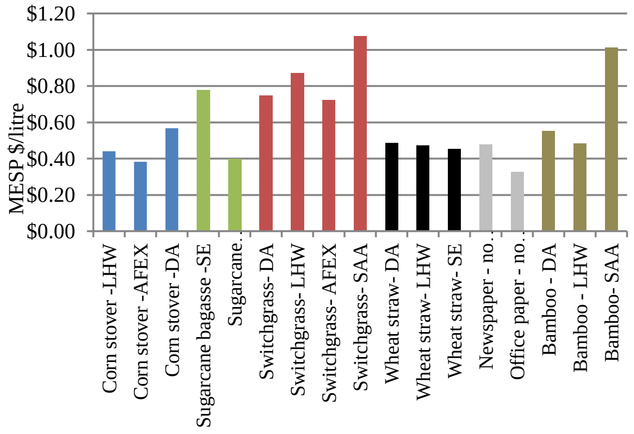

Fig. 4 Comparison of MESPs for bioethanol from bamboo and other biomass feedstocks (Corn stover- LHW and AFEX [39]; Corn stover-DA[13]; Sugarcane bagasse-SE and Sugarcane sugar + bagasse-SE [40]; Switchgrass-DA, LHW and AFEX [41];Wheat straw-DA, LHW and SE [42]; Newspaper- and Office paper-no pretreatment [37])

As a comparison, this data is compared against other techno-economic analyses evaluating the cost of ethanol production from various lignocellulosic feedstocks and subjected to different pretreatments (Fig. 4).

A wide range of MESPs from 0.327 $/litre to 1.075 $/litre is reported, which reflect the differences in feedstock composition and processing route. The results for bamboo-derived bioethanol using LHW, DA and SAA pretreatments, at 0.484 to 1.014 $/litre are within this range. Moreover, similar trends between the pretreatment technologies are demonstrated, reflecting that on average, using LHW and DA pretreatments results in a lower cost of bioethanol than with SAA pretreatment [38].

3.2 Environmental profile of bamboo-derived bioethanol

LCA results for 'well-to-gate' analysis on bioethanol from bamboo using three pretreatment technologies are presented in Table 6 and their contribution analyses are shown in Fig.5

In Fig. 5, the 'above-the-line' scores represent environmental burdens, whilst 'below-the-line' scores represent environmental savings such as carbon sequestered in bamboo biomass and the avoided emission credits from the surplus electricity. In the three bioethanol production pathways, most impact categories (ADP, AP, ODP, HTP, and POCP) show that enzyme production is a significant contributor due to the high energy consumption required, most of which is natural gas. For AP, the significant contribution from combustion is a result of the SO_2

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emissions converted from sulphur in the bamboo feedstock, as well as the sulphuric acid used in pretreatment, particularly for DA pretreatment. For GWP_{100}, the main contribution comes from CO_2 emissions derived from biogenic carbon, which is offset by C sequestration in bamboo. In addition to combustion, bamboo cultivation is also a main contributor to EP because of N_2O field emissions and fertilizer production. For ODP, which refers to the decrease in the total volume of ozone in the Earth's atmosphere, ammonia production is the dominant contributor to the pretreatment process in DA and SAA pathways, whilst herbicide production is the main reason for the score of bamboo cultivation. For ecotoxicity impact categories (HTP, FATEP, and TEP), environmental burdens from the 'Bamboo cultivation' process are mainly due to herbicide production whilst whose from the 'Pretreatment' process are from acid and ammonia production. For TEP particularly, caustic is the main contributor to the score of the WWT process. For POCP, burdens in enzyme production and bamboo cultivation are due to emissions from fossil fuel consumption, whereas those in combustion are from SO_2 emissions. Overall, the credits from surplus electricity offset the 'above-the-line' scores of all impact categories considerably, resulting in relatively low net burdens or even negative scores (Table 6).

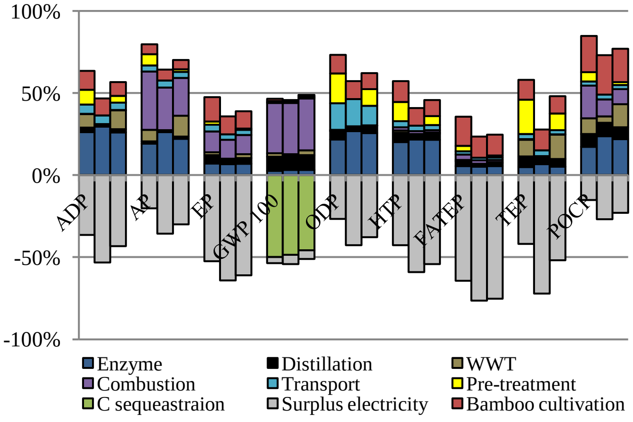

Fig.5 Contribution analysis of environmental profiles for bioethanol from bamboo with DA (left column), LHW (middle column) and SAA (right column) pretreatments (Unit: '*1kg of ethanol produced from bamboo*')

Table 6 LCA results for three bamboo bioethanol pathways

Impact category	DA	LHW	SAA
ADP, kg Sb eq./FU [a]	3.55E-03	-1.18E-03	4.55E-03
AP, kg SO_2 eq./FU	8.58E-03	4.66E-03	1.24E-02
EP, kg PO_4 eq./FU	-1.76E-04	-1.65E-03	-2.11E-03
GWP, kg CO_2/FU	-1.23E+00	-1.83E+00	-8.18E-01
ODP, kg, CFC^{-11} eq./FU	4.78E-08	1.87E-08	6.13E-08
HTP, kg 1,4 –DB eq./FU	1.01E-01	-1.83E-01	-1.43E-01
FATEP, kg 1,4 –DB eq./FU	-1.37E-01	-4.25E-01	-6.38E-01
TEP, kg 1,4 –DB eq./FU	1.15E-03	-3.62E-03	-8.96E-04
POCP, kg C_2H_4 eq. /FU	5.29E-04	3.93E-04	8.34E-04

Note: [a] FU=Function unit, '*1kg of ethanol produced from bamboo*'.

In order to compare with petrol, a 'well-to-wheel' LCA analysis was also performed, by including the fuel consumption process in a FFV passenger car (Fig.6).

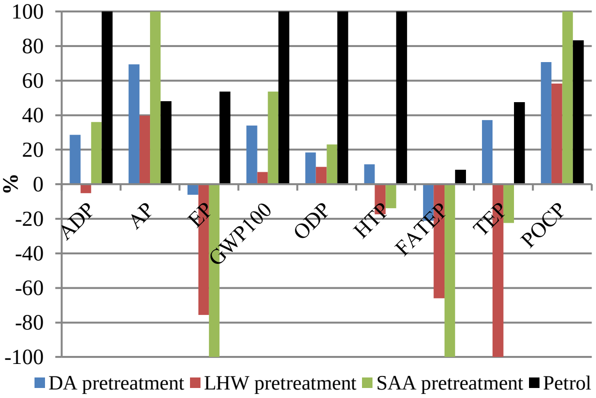

Fig. 6 Characterised LCIA comparison results for bamboo-derived ethanol with petrol (Unit: '*1km travelled in a FFV*')

In Fig.6, negative scores found in some of the impact categories are due to the significant credits from the electricity generated. In general, all three bioethanol production pathways are environmentally better than petrol, with significant advantages in EP, GWP_{100}, ODP and ecotoxicity categories. Among these three pathways, LHW pretreatment delivers the lowest environmental burdens except in the impact categories of EP and FATEP, resulting in the best overall pretreatment technology from an environmental perspective. With regards to GHG emissions, the results reveal a GHG emissions saving ranging from 45% to 93% by using bamboo-derived bioethanol instead of petrol.

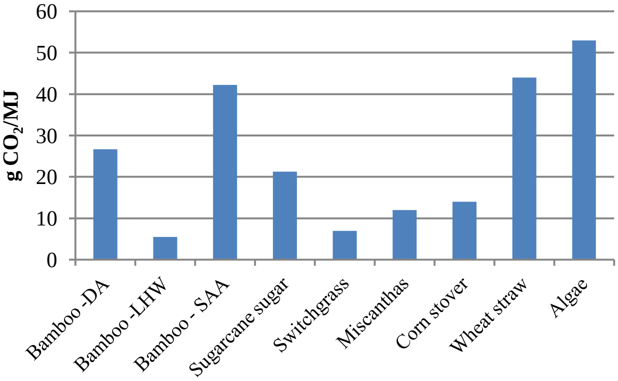

Fig.7 'Well-to-wheel' GHG emissions for bioethanol produced from various biomass feedstocks (Unit: '1 MJ bioethanol'; Sugarcane sugar [43], Switchgrass [44], Miscanthus [44], Corn stover [45], Wheat straw [46], Algae [47]).

Several LCA analyses for GHG emissions of bioethanol from various biomass feedstocks have been reported in literature and are compared with our findings in Fig.7. The functional unit for 'well-to-wheel' comparison is '1 MJ bioethanol' to keep consistent with other studies. Fig.7 shows that the GHG emissions for bioethanol from various biomass feedstocks are

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in the range of 5.5 – 53 g CO_2 eq./MJ ethanol. Bamboo-derived bioethanol with LHW pretreatment is found to have the lowest GHG emissions (5.5 g CO_2 eq./MJ ethanol), indicating that bamboo could be a very promising feedstock for bioethanol production from an environmental perspective.

4 Conclusions

Techno-economic and environmental assessments are performed on bioethanol from bamboo using three different pretreatment technologies (Dilute acid, liquid hot water and soaking in aqueous ammonia) in the present study. By applying a relatively low enzyme loading of 10 FPU/g glucan, annual bioethanol production rates are 179 million litres for DA, 147 million litres for LHW and 95 million litres for SAA pretreatment. By factoring in the credits from the amount of electricity generated and sold in these three technology scenarios, the MESPs for them are 0.554 $/litre, 0.484 $/litre and 1.014 $/litre respectively. The cost breakdown analysis reveals that the capital cost is the biggest contributor followed by the bamboo feedstock cost. The bamboo-derived bioethanol pump price is also calculated taking into account other pump price parameters such as distribution cost, taxes and subsidies, and is compared with petrol. Two scenarios (current and future with removal of government support) are considered. Bamboo-derived bioethanol using DA and LHW pretreatment technologies are found to be economically competitive with petrol in both current and future policy scenarios, whilst that from SAA pretreatment failed to compete with petrol even with government support.

A life cycle assessment on bamboo-derived bioethanol was carried out to evaluate these bamboo-to-bioethanol processes from an environmental perspective. The ‘well-to-gate’ contribution analysis shows that enzyme production and bamboo cultivation are the main contributors to most impact categories, whereas CHP and pretreatment processes are also significant contributors to related impact categories (*i.e.*P_{100} and POCP etc.). The bioethanol production using three pretreatment technologies are compared with petrol on a ‘well-to-wheel’ basis. It is found that all three bioethanol pathways are environmentally better than petrol, with LHW delivering the best environmental profile of a GHG emissions saving of 93% against conventional petrol.

Bamboo-derived bioethanol is also compared with bioethanol from other biomass feedstocks from both economic and environmental perspectives. It concludes that bamboo is a very promising feedstock for bioethanol production and suggests that liquid hot water pretreatment method could result in the lowest production cost and best environmental profile among three pretreatment technologies studied in this paper.

Notes and references

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1. L. D. Gomez, C. G. Steele-King and S. J. McQueen-Mason, *New Phytologist*, 2008, **178**, 473-485.
2. P. Al-riffai, B. Dimaranan and D. Laborde, European Union and United States Biofuel Mandates - Impacts on World Markets in *Inter-American development bank*, 2010.
3. IEA, World Energy Outlook, 2010, Paris, France, IEA/OECD.
4. M. Lobovikov, S. Paudel, M. Piazza, H. Ren and J. Wu, World bamboo resources - A thematic study prepared in the framework of the Global Forest Resources Assessmet 2007, Rome, Italy, Food and Agriculture Organization of the United Nations.
5. J. M. O. Scurlock, D. C. Dayton and B. Hames, *Biomass and Bioenergy*, 2000, **19**, 229-244.
6. M. E. Himmel, S.-Y. Ding, D. K. Johnson, W. S. Adney, M. R. Nimlos, J. W. Brady and T. D. Foust, *Science*, 2007, **315**, 804-807.
7. J. D. McMillan, Pretreatment of lignocellulosic biomas in *Enzymatic conversion for biomass for fuels production*, eds. M. E. Himmel, J. O. Baker and R. P. Overend, DC: American Chemical Society, Washington, 1994, p. 292-324.
8. H. Jørgensen, J. B. Kristensen and C. Felby, *Biofuels, Bioproducts and Biorefining*, 2007, **1**, 119-134.
9. P. Kumar, D. M. Barrett, M. J. Delwiche and P. Stroeve, *Industrial & Engineering Chemistry Research*, 2009, **48**, 3713-3729.
10. Z.-Y. Sun, Y.-Q. Tang, T. Iwanaga, T. Sho and K. Kida, *Bioresource Technology*, 2011, **102**, 10929-10935.
11. Y.-N. Wang, C.-H. Ko, C.-Y. Lee, H.-P. Tsai, W.-H. Chen, W.-S. Hwang, M.-J. Tsai and F.-C. Chang, Evaluation of bamboo as a feedstock for bioethanols in Taiwan, in *World Renewable Energy Congress*, Linkoping, Sweden, 2011.
12. J. Littlewood, L. Wang, C. Turnbull and R. J. Murphy, *Biotechnology for biofuels*, 2013, **6**, 173-186.
13. D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu and A. Aden, Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol, 2011, National Renewable Energy Laboratory (NREL).
14. J. Littlewood, Potential for bamboo as a feedstock for lignocellulosic biofuel production, 2014, London, Imperial College London, pp. 201.
15. Y. Ding, Personal Communication, Cost of waste bamboo material, Littlewood J, 2012.
16. BAIINFO, BAIINFO Fertilizer Weekly, http://www.baiinfo.com/MBC/index.html, Accessed August, 2012.
17. F. K. Kazi, J. A. Fortman, R. P. Anex, D. D. Hsu, A. Aden, A. Dutta and G. Kothandaraman, *Fuel*, 2010, **89, Supplement 1**, S20-S28.
18. BAIINFO, BAIINFO Sulfuric Acid Weekly, http://www.baiinfo.com/MBC/index.html, Accessed August, 2012.

RSC Advances Accepted Manuscript

19. China fertilizer net, Liquid ammonia prices sharply higher http://www.chinahaoyuan.com/eindex.php/trade_news/id-5472.html Accessed May, 2012.
20. Alibaba.com, Factory sale 98% calcium oxide http://www.alibaba.com/product-gs/216902509/factory_sale_98_calcium_oxide.hml Accessed March, 2013.
21. Chemical market associates Inc. CMAI, Global chlor-alkali market report, http://www.cmaiglobal.com/marketing/samples/cmr_summary.pdf, Accessed August, 2012.
22. G. Raball and P. Macchi, Transport prices and Costs: The need to revisit donors' policies in transport in Africa, in *14th BREAD Conference on Development Economics*, Chicago, IL, 2008.
23. Nanning federation of industry and commerce, An introduction to Nanning investment environment, http://www.nngsl.org/16/2011_4_1/16_70_1301639511125.html, Accessed March, 2012.
24. Y. Sun, Biomass baby keeps on growing. China Daily: Europe, http://europe.chinadaily.com.cn/epaper/2012-04/13/content_15042541.htm, Accessed March, 2012.
25. KPMG, Corporate and Indirect Tax Survey, http://www.kpmg.com/Global/en/IssuesAndInsights/ArticlesPublications/Documents/corporate-and-indirecttax-rate-survey-2011.pdf, Accessed August, 2011.
26. ISO 14040, Environmental management-Life cycle assessment-Principles and framework 2006.
27. PRECONSULTANTS, Simapro 7 Database Manual Methods Library, 2010.
28. P. Van Der Lugt, A. Van Den Dobbelsteen and R. Abrahams, *Journal of Bamboo and Rattan*, 2003, **2**, 205-223.
29. Ecoinvent. Swiss Centre for Life Cycle Inventories (Ecoinvent Centre), Ecoinvent database, Ecoinvnet Centre Dubendorf, 2007.
30. IPCC, IPCC Guidlines for National Greenhouse Gas Inventories., 2006, Japan, Institute for Global Environmental Strategies.
31. EPA, Exhaust Emission Factors for Nonroad Engine Modeling-Spark-Ignition, 2010, U.S. Environmental Protection Agency.
32. A. M. Nielsen, *The inventory of Cellic Ctec enzyme*, Wang L, Novozyme A/S Denmark, 2010.
33. P. A. Beauchemin and M. T. Tampier, Emissions from Wood-Fired Combustion Equipment, 2008, North Vancouver, British Columnbia, Envitrochem service Inc.
34. S. W. Grass and B. M. Jenkins, *Biomass and Bioenergy*, 1994, **6**, 243-260.
35. EMEP/CORINAIR, *Atmosperic Emission Inventory Guidebook - 3rd Edition*, European Environment Agency, 2003.
36. S. Korhonen, M. Fabritius and H. Hoffren, Methane and Nitrous Oxide Emissions in the Finish Energy Production, 2001, Finland, Fortum Power and Heat Oy, Technology Ltd.
37. L. Wang, M. Sharifzadeh, R. Templer and R. J. Murphy, *Energy & Environmental Science*, 2012, **5**, 5717-5730.
38. R. R. Scott and J. Junyang, China-Peoples Republic of, biofuels 2011 annual report. in *Global Agricultral Information Network (GAIN) Report*, ed. Service UFA, 2012.
39. T. Eggeman and R. T. Elander, *Bioresource Technology*, 2005, **96**, 2019-2025.
40. S. Macrelli, J. Mogensen and G. Zacchi, *Biotechnology for biofuels*, 2012, **5**, 22-40.
41. L. Tao, A. Aden, R. T. Elander, V. R. Pallapolu, Y. Y. Lee, R. J. Garlock, V. Balan, B. E. Dale, Y. Kim, N. S. Mosier, M. R. Ladisch, M. Falls, M. T. Holtzapple, R. Sierra, J. Shi, M. A. Ebrik, T. Redmond, B. Yang, C. E. Wyman, B. Hames, S. Thomas and R. E. Warner, *Bioresource Technology*, 2011, **102**, 11105-11114.
42. J. Littlewood, R. J. Murphy and L. Wang, *Renewable and Sustainable Energy Reviews*, 2013, **17**, 291-300.
43. J. E. A. Seabra and I. C. Macedo, *Energy Policy*, 2011, **39**, 421-428.
44. C. D. Scown, W. W. Nazaroff, U. Mishra, B. Strogen, A. B. Lobscheid, E. Masanet, N. J. Santero, A. Horvath and T. E. McKone, *Environmental Research Letters*, 2012, **7**, 014011.
45. S. Spatari, Y. Zhang and H. L. MacLean, *Environmental Science & Technology*, 2005, **39**, 9750-9758.
46. L. Wang, J. Littlewood and R. J. Murphy, *Renewable and Sustainable Energy Reviews*, 2013, **28**, 715-725.
47. E. D. Frank, J. Han, I. Palou-Rivera, A. Elgowainy and M. Q. Wang, *Environmental Research Letters*, 2012, **7**, 014030.

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